



## PHD

**Time cost models: Their use in decision making in the construction industry with particular reference to the use of the microcomputer.**

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TIME COST MODELS: Their Use in Decision Making in the Construction Industry with Particular Reference to the Use of the Microcomputer.

Thesis submitted by: Matthew M Cusack MPhil FBIM MCIOB MEnvSc  
for the Degree of Doctor of Philosophy of the University of Bath.

1981

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With Particular Reference to the Use of the Microcomputer

ABSTRACT

This thesis investigates the current approach to decision making in the construction industry with its background of uncertainty in relation to such factors as workload, production methods, resource availability and profitability. Given this situation, and the less than deterministic environment that usually surrounds the construction project, effective planning and control procedures are seen as a prime necessity and not as a luxury. Within this context, the most significant decisions relate to the time and cost parameters and more specifically to their inter-relationship and the need to provide optimal or near optimal solutions to this relationship. A preliminary feasibility study was conducted in conjunction with six building construction companies operating in the United Kingdom. This indicated that the potential for substantial benefits exist and was further substantiated by replies received to a questionnaire circulated to one hundred additional construction companies. The time and cost parameters are investigated and the related decision problem formulated in a quantitative manner. Existing models are examined and three alternative models are postulated, viz. an integer linear programming model - this model, like the existing models studied, is difficult to implement due to the large number of variables and constraints involved; an integer linear programming model based on breakthrough points on the cost curve (since the number of breakthrough points is less than the number of points of discontinuity, there are fewer integer variables) and a heuristic model capable of dealing with the problems associated with non-linear time cost curves using a microcomputer. Appropriate programs are developed for use on a CBM 32K microcomputer with a dual drive floppy disk system and high speed printer. Both the integer linear programming models and the heuristic model are tested using simulated project data. Comparative tests indicate that the heuristic model, although adopting a simpler method of analysis, is capable of providing a solution comparable in accuracy with the more sophisticated integer linear programming model. The computer system is designed to permit the data to be structured in several different ways depending on the needs of the recipient, ie., the person who makes the decisions receives only that part of the output that is relevant to their action.



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## CHAPTER 1. INTRODUCTION

### 1.1 The Problem

Choosing between alternative courses of action is a distinguishing human attribute and it is clear that decision making has now emerged as a new independent discipline with its own laws and methods.

There are, in existence, two basic theoretical approaches - the behavioural approach and the management science approach. In the former the decision making process is investigated to establish the various stages through which the human mind goes, before a particular course of action is taken. It attempts, therefore, to identify why people behave in a certain way and to predict from their past behaviour their likely action in the future. It is, thus, a subjective approach to decision making.

The management science approach is rather more difficult to summarise in terms of a predictive decision theory. There is a vast amount of published literature and it could be argued that all books on operational research and applied mathematics fall directly or indirectly into this area of study. It must be accepted however, that whatever the numerical technique considered appropriate, there are still a number of logical stages through which the decision maker must go to enable him to arrive at a final decision. A decision making model can be identified when there are two or more possible courses of action, each leading to one or more possible outcomes.

Decisions are made to attain an objective or a desirable state of affairs. Usually in an industrial or commercial organisation the objective is the optimisation of a particular function expressed in monetary terms. If the function is a profit-making one, then the optimisation is a maximisation. If on the other hand, it is a cost, the optimisation is, in fact, a minimisation. A major objective therefore, of a company might well be to complete a particular contract in a minimum period of time. Such a decision might well mean crashing the time and therefore increasing the first cost of the project. There are, of course, many instances where an objective cannot be expressed in monetary terms only, for instance, maintaining the reputation of a company may require completion on time, and the prospects of future contracts may well be more important than a minimal loss brought about by the crash programme designed to meet a specified project date for a particular contract.

If there is only one possible action open there is no decision problem, unless, of course, the decision maker can opt to take no action whatsoever. If, however, the decision maker has to select from two or more courses of action, then of course a decision problem does exist. Such a situation might exist when making decisions on whether to hire, buy or operate within the existing level of plant resource. If there is no finance available for purchase of equipment, then no decision problem exists. If finance is available, there will be a decision as to whether to hire or buy plant. A third decision might revolve around the proportion of plant being bought or hired. The outcome of a decision is ultimately measured against the degree to which it satisfies the objective and solves the particular problem. Virtually all decision problems in the construction industry include an element of both the time and cost parameters.

Resulting from the current economic problems facing the construction industry, there has been a considerable reduction in the number of new projects available for tender. Accordingly, increased competition for a share of a reducing market has inevitably led to a lowering of profit margins. Higher levels of productivity are necessary to offset this situation, entailing greater managerial efficiency and decision making ability. Construction management, in controlling both the physical project and the construction process, is often forced to make important decisions based only on intuition and experience. This may be due to such factors as the inadequacy of the information available, the high cost or complete absence of an objective method of analysis, the diversity of the forms in which the problems actually arise, the intellectual ability of the personnel concerned or a combination of these factors. There may, of course, be other equally significant factors. Therefore, the ones highlighted are illustrative in nature only but are considered to be particularly significant in terms of this research.

As mentioned above, the most important decisions in the construction industry invariably relate to the parameters of time and cost. While it is unlikely that practitioners would dispute this premise, there is clearly a lack of understanding of the significance of the time cost relationship.

Several attempts have been made to model these two parameters over the past two decades and researchers have identified and examined the relationship that exists between them. These attempts have met with limited success, the more specific reasons for which, are discussed in the body of the research.

Returning to the problem of availability of suitable data referred to above, it would appear that there is, if anything, an excess of data available to managers in the construction industry as a basis for decision making. What is lacking is an objective method for modelling the data and an accurate, quick and economic way of analysing it. Equally, the output must be presented in such a way as to satisfy the intellectual ability and needs of the recipient. It must also be capable of reflecting the uncertain nature of the construction process through ease of amendment and updating facilities. The general problem to which the research addresses itself can therefore be defined as - the significance of the time cost parameters and their relationship to decision making and more specifically the design of time cost models that can be analysed using the computational and low cost features of the micro computer.

## 1.2 Conceptual Basis for the Research

It is necessary, however, to provide a conceptual basis for the research, i.e. a specific purpose or function to be satisfied by solving the problem. Concept development is seen as falling into four categories, viz:

- i. Concept research - little awareness of concept in industry - no evidence of use. Limited research only, based on complex models requiring high powered computers for their solution.
- ii. Concept innovation - adequate research has been performed and an awareness in industry established.
- iii. Concept implementation - in high use in industry, concept has been widely accepted. Industry acceptance through innovation, word of mouth and other lines of communication.
- iv. Concept fully researched and accepted - in high use in industry, concept is in general use, adequate research has been performed on the idea. Inadequate knowledge has been established to show the concept's effectiveness.

It is considered that the proposed research falls, in the first instance, into category i. above, in that:- a) there is only a very limited awareness of the significance of the concept in industry (see Section 1.6); b) the complex nature and questionable value of published research work to date, i.e. intellectual capacity of user; c) the need for a large high powered computer facility, i.e. high cost of analysis.

In addition, a further measure of the value of the research could be seen as its potential to achieve cost savings, i.e. cost effectiveness. Finally, the formulation of the mathematical models required to analyse the time cost relationship is indicative of the academic rigour of this research. This research is therefore first concerned with Concept i. and subsequently Concept ii. - Concepts iii and iv are seen as extensions of this program requiring further research and external funding.

### 1.3 The limited acceptance of management science and computer based production systems in the construction industry

The research will draw mainly on those aspects of the management science approach and to a lesser extent, the behavioural approach, that are fundamentally concerned with influencing and improving decision making and dealing with complex situations. It has been suggested that these areas constitute the most basic dilemmas facing the construction industry, a view that has been substantiated by pre-research discussions undertaken to establish the feasibility of the proposal. This must not, however, be construed to support the general view that the construction industry, as a whole, is backward and resists innovation and change as this view is considered to be superficial and to a large extent, incorrect. It is true to say that a number of construction firms have responded positively to change within the constraints in which they operate, their production capacity has grown in spite of shrinking resources, and they have extended their overseas markets with a high level of success, in the face of strong competition.

The construction industry has, however, been slow to accept and apply the findings of research undertaken using management science techniques.

Larew<sup>1</sup> who sees the basic problem as relating to the financing of research suggests that "some excellent work has been done but even this work, which is largely unsupported, has not been disseminated promptly and widely to interested persons in construction". Mayren<sup>2</sup> states that "the only management method that has been consistently applied in the construction industry is network analysis". He goes on to say that "research achievement should be five to ten years ahead of the industry, but the sad truth is that the latter does not employ the tools developed by science ten years ago".

Bjornsson<sup>3</sup> considers that part of the problem is due to the fact that "recently graduated construction engineers trained in playing the numbers game rushed out to rescue the industry from a sub-optimal behaviour .... problems for analysis are defined and selected in such a way that the method cannot be applied. Secondary consideration being given to the severity of the

problem and the assessment of the appropriateness of the systems technique". He adds that "the acceptance and use of quantitative methods in the construction industry is still very limited. These methods may be acceptable to some engineers who have learnt to use them to gain a better insight into complex technical and economical processes. But the more complex the analysis, the less likely they are to be able to convey their feelings to top management who are not prepared to rely on methods they cannot grasp and understand".

It can be seen, therefore, that the failure of the industry to accept quantitative methods of analysis is considered to be due, not only to a resistance to innovation but a failure on the part of researchers to express their findings in a fashion that can be understood by the less numerate.

It is the intention of this research, therefore, to produce models that are predictive, but in no way, explanatory. The aim being to provide an effective aid to management decision making without detriment to professional judgement and experience. The computational and analytical power of the computer is obviously of great significance in solving complex problems involving vast quantities of data. Gil, investigating "the reasons why the different computer systems in existence for many years now have remained purely academic and did not find their proper place in the construction industry", suggests that "a major reason for their non-acceptance or perhaps unacceptability is the vast amount of computer print-outs that are produced. Executives are so busy that their instinctive reaction is to ignore this additional paperwork". A further factor is the high cost and difficulties associated with the use of computers on construction sites. An additional aim, therefore, is to investigate the potential of the micro computer in this respect and take advantage of the interactive nature of this equipment to reduce the volume of paperwork.

Certainly the development of management science techniques and of computing facilities have provided decision makers, at different levels, and in many types of organisations, with a wide variety of aids to improve their performance. While it is recognised that there are still many decisions - and amongst them some of the most important, that must rely on subjective assessments based on intuition and past experience, it is believed that many others can be quantified. A third category also exists which does not fall wholly in either of these classifications but is an amalgam of both quantifiable and unquantifiable elements. It is felt that the application



of objective models as a basis for decision making could be used more frequently than past research has suggested to improve decisions relating to the time cost parameters, and more specifically, their interrelationship.

#### 1.4 The Objectives of the Research

- i. To examine, in general terms, the decision making procedures in use and identify the major stages of decision making in the construction industry.
- ii. To examine, in detail, the parameters of time and cost, identify their interrelationship and establish their value in the decision making process.
- iii. To model the time cost relationship in a) formal mathematical terms, and b) a heuristic form designed to utilise the characteristics of the micro computer.
- iv. Evaluate the potential of the micro computer in terms of economy, computational and analytical capacity and practical acceptability, in relation to objectives i), ii), and iii), above.

#### 1.5 Structure

Research of this type does not follow an orderly hypothesis - experiment-conclusion sequence in that the experiments and interim conclusions tend to result in periodic redefinition of the hypothesis. The problem under consideration has several components each with their individual responses. This is reflected in the different objectives identified above and influences the structure of the thesis. To provide a logical exposition, the thesis is divided into seven chapters. Chapter 1 acts as the introduction; Chapter 7 presents the conclusion; Chapters 2,3,4,5 and 6 comprise the body of the thesis.

Chapters 2,3,4,5 and 6 each commence with an introductory section. These sections provide the transition between the chapters and relate each to the general problems and objectives.

Chapter 1 states the general problem, delineates the objectives, outlines the structure of the thesis and summarises discussions and correspondence with the sample companies.

Chapter 2 is introductory in nature and is concerned (in conjunction with Chapter 3), with providing a conceptual basis for the research through an examination of the structure of the industry, the decision makers and

major decision areas concerned and an evaluation of appropriate decision theories.

Chapter 3 examines the functions of planning and control and gives detailed consideration to the characteristics of activity and project duration and direct and indirect costs in the context of these two functions.

Chapter 4 considers the interrelationship between the time and cost parameters, looks at the problem of modelling the interrelationship and highlights the limitations of existing models.

Chapter 5 is concerned with developing a new approach to modelling the time cost relationship and the determination of minimum project costs associated with each feasible duration of a multiple activity project. Three alternative models are proposed.

Chapter 6 looks initially at the development of computer based production systems. The micro computer hardware used and the software developed is described and the models postulated in Chapter 5 are tested and evaluated using simulated data.

Chapters 7 and 8 present the general and final conclusions of the research and suggest areas for further research.

## 1.6 The Sample Companies

In order to ascertain the "state of the art" and provide background information and assist in the provision of a conceptual basis for the research, six sample companies were consulted. In addition, one hundred companies were circulated with a questionnaire. (Appendix 4 ). The six companies selected for special study were all large, with an annual turnover in excess of £30m. It was considered that only the larger companies were likely to adopt sophisticated methods of planning and control due to the large and complex nature of the projects with which they were concerned. They therefore provided the range of conditions conducive to a study of decision making procedures and possessed some or all of the following characteristics:

- i. They are all engaged in building and civil engineering works.
- ii. With one exception, they undertake work overseas in addition to the United Kingdom.
- iii. They obtain the highest proportion of their work by competitive bidding but all engage in other forms of tendering.

- iv. The highest proportion of the tenders and later cost control procedures are based on the Bill of Quantities.

The initial objective was, therefore, to establish a profile (see Appendix 1), for each company as a basis for obtaining answers to such questions as:

What decisions are made in relation to the selection of market areas and bidding strategies?

What decisions are made by estimators and planners in determining the initial net cost of the contract?

What decisions are made by the Board of Directors when arriving at the final tender figure?

What decisions are made by planners, site managers, etc. when the contract has been awarded and production has commenced?

What amount of time is available and what time is actually spent on decision making at these three stages?

Who is responsible for decisions made at these various stages?

In what way do the decisions made at these various stages interrelate and influence one another?

What objective are the decision makers trying to achieve at each stage?

What information is required and what information should be available in an ideal situation at each stage?

What sources of information are available within the company?

What information must be obtained from external sources, eg. design decisions over which contractor has no influence?

With one exception the companies wished to remain anonymous, therefore, for consistency, they are referred to as Companies A, B, C, D, E and F.

To ensure a representative sample, it was thought initially that it might be necessary to approach a larger number of companies direct. However, the initial visits indicated that there was so little differentiation between the companies and the product with which they were concerned that it proved unnecessary to extend this aspect of the study further. Outline profiles of two individual sample companies are given in Appendices 2 and 3.

The identification of the decision making process and the decision makers

themselves presented no real difficulties and the role of the decision makers as perceived by top management was ultimately confirmed by the individual decision makers themselves in all the companies studied.

In terms of time and cost, there appeared to be no lack of data. However, generally speaking, it was not present in a form that could be easily adapted to form a basis for decision making. Had it been available in this form, there did not appear to be any quantitative models or methods apart from the usual bar charts or occasionally a network diagram available to analyse the data. It seemed, in fact, that the more important the problem, the greater the tendency to arrive at a decision purely on intuition and experience.

Responsibility for major decisions rested in all cases with the Board of Directors, the senior estimator/s or quantity surveyor/s, the senior planner/s, the project manager/s and occasionally the plant manager/s. It was apparent that not only were the objectives of these groups of decision makers, within an individual organisation, different but that they were often in conflict. In fact, the objectives of a specific individual group could be contradictory in nature, i.e. major objectives of the Board of Directors might well be to minimise both project duration (time) and project spending (cost). These two objectives are often contradictory and the merits of each therefore, require evaluation and optimising to determine the most appropriate solution in the particular circumstance. When, as is often the case, a plant department operates as an independent entity it will naturally establish the need to maximise profits as a major objective to justify its existence. This objective, however, will be in conflict with an objective of the main Board of Directors, which sets out to minimise project spending. Conversely, the planners will select plant that will complete a project or activity in the minimum time, seeing this as one of their main objectives. Accordingly, they may decide to hire plant from an external organisation, once again creating a situation of conflict between decision makers, i.e. planners and plant managers.

While recognising this conflicting and often contradictory approach to decision making within the sample companies it was felt that it in no way changed the research objectives. In fact, it highlighted the need to quantify certain aspects of the decision making process, to provide a more objective basis on which the decision makers could compare their objectives, enabling them to act in a more corporate manner.

Decisions made by planners (time) and estimators (cost), tended to have a more quantitative base than the other groups, particularly in relation to individual contracts. It was decided accordingly to slant the major aspects of the research towards the operational aspects of individual contracts, at the same time retaining its applicability to other areas of decision making, ie. pre-tender.

When the operational stage of a contract is reached further conflicts arise when site management, whose major objective will be to operate within defined cost and time limits, find that the schedules established by the planners prevent this from being achieved. These conflicting goals, which relate mainly to time and cost, must be recognised. They can only be reconciled when the plan is flexible and the facility exists for rapid updating and re-analysis of the problems as they arise.

It was apparent from discussions with the sample companies that the approach adopted tended, in the main, to emphasise the individual components of a problem, rather than focussing on the objectives of the overall problem. This is particularly true in the case of the time cost problem where each parameter is investigated separately, but no attempt made to examine, analyse and optimise the relationship between the two. Generally the groups responsible for decision making found it difficult to accept the fact that in certain circumstances, in order to optimise the overall problem, certain of the problems components will, of necessity, be less than optimal, e.g. the maximisation of profit will not always be possible in the case of the plant department.

The company profiles included in Appendices 2 and 3 are indicative of the type of information obtained from the initial visit to the sample companies. Several subsequent visits were, of course, necessary to complete the more detailed information required as the research developed. The information, assistance and advice gained in this way is incorporated in the body of the research and is therefore analysed within the appropriate areas of study.

#### Companies Consulted by Questionnaire

In order to obtain a broader range of answers to certain specific questions, one hundred companies were circulated with the questionnaire shown in Appendix 4. Forty replies were ultimately received. Twenty smaller companies were included in the mail shot and it was apparent from the information requested in Part I - Section 1.1 of the Questionnaire, that very few of these replied. The variance in size of the companies replying in terms of turnover and number of employees ranged from £120,000 to

to £400m and 10 - 15,000 respectively. Eight of the companies had turnovers in excess of £100m and fourteen had turnovers of less than £10m. Of these only one had a turnover of less than £1m. Eleven companies employed more than 1,000 people and fourteen employed less than 500 people. Of these four employed less than 100 people. This brief information is not intended to convey other than a general impression of the scale at which the various organisations were operating and accordingly, the representative nature of the sample.

The majority of the companies embraced the range of activities defined in the Questionnaire. (Appendix 4). It is interesting to note that as many as twenty eight companies were concerned with Design/Construct packages. The general problem caused by the divorce of design and production is, of course, obviated in this situation.

The affirmative replies to the questions set out in Parts 2,3,4 and 5 of the Questionnaire are summarised in Appendix 4. Thirty five companies confirmed that they prepared a formal programme showing the sequence, interrelationship and duration of project activities. Of these, thirty two used bar chart methods of presentation. Eighteen using this technique exclusively. Sixteen used CPM and six companies used the technique PERT. Of the six using PERT, it is interesting to note that with one exception, they also used both the CPM and bar chart techniques. All of the companies using CPM used it for post contract planning, however, only five used this technique for pretender and/or short term planning. Of the six companies using PERT, all used it for post contract planning, five used it for pretender planning and four for short term planning. It can be seen, therefore, that the bar chart method of presentation is the one used most extensively. The basic reason for this being the ease with which it is understood and accepted at site level. It does not, however, impose the discipline of defining the logic in the way implicit in the CPM and PERT approaches and it is extremely difficult, if not impossible, to change and update a plan that is not clearly defined in this way. It is also difficult to express the relationship between time and cost on a bar chart (see Chapter 4), and virtually impossible to vary the time cost relationship due to the lack of information displayed.

It is also interesting to note that CPM and PERT are not used to any great extent for pretender and short term planning. It would appear that the principle reason relates to the short time scale available for pre-planning and testing alternative courses of action. In the case of

pre-tender planning, the time scale for presenting a tender is rarely longer than one month. It is, however, difficult to see how a realistic tender can be submitted when alternative methods of combining time and cost cannot be explored and presented as an essential feature of the decision making process at this stage. In the case of short term planning, the nearer to the actual occurrence at which a decision is made and the effect of alternative approaches analysed, the greater is the likelihood of accuracy. Therefore, in both cases, the lack of an objective facility backed up by the computational speed of the computer is seen to be a major factor inhibiting the use of CPM and PERT at other than the post contract planning stage.

Thirty one of the companies concerned operated a cost analysis control system. As might be expected, twenty seven based their system on the Bill of Quantities. As explained in Chapter 2, this approach makes it impossible to adequately relate the time and cost parameters. It was interesting to see the comparatively high number of companies using work measurement as a basis for cost analysis and control. Surprising, that is, in that the question referred to the form of the work measurement used in work study. However, further investigation indicated that the replies referred to records kept by site personnel, mainly operatives who are notoriously unreliable in this respect. In retrospect, the question should have referred more directly to work study techniques. Six of the large international companies were using genuine work study techniques or a sophisticated variation (see also other approaches, Appendix 4).

Again, in retrospect, Question 4.1, Part 4 also proved to be confusing. The intention was to seek information as to those companies operating a system that sought to achieve optimal or near optimal solutions to the inter-relationship between the time and cost parameters. It was felt, however, at the time of issue of the questionnaire, that detailed reference to a sophisticated approach to the problem aimed at optimising the relationship would possibly confuse the recipients of the questionnaire. As a result of several phone calls received and further investigation, it transpired that only five of the very large companies indulged in an analytical attempt to relate the two factors and even then the approaches used were limited and, in the main, not applied at site level. Of the others, the answer YES was more an acceptance of such factors as "time means money" and vice versa, e.g. "overtime was expensive and although (and this is debateable), it speeded up the contract, it increased the cost to the contractor" (again a debateable point).

Six of the companies used main frame computers (4.1b), owned by the company as a basis for determining the time cost relationship. This statement must, however, be judged in the light of the preceeding paragraph. Certainly, the four international companies did have a system, but as stated, this rarely extended to the site situation. It is interesting to note that none of the companies were using micro-computers, although two did add the rider that they were exploring the possibility. One company had based their system on PERT, one on CPM, and two had evolved a hybrid system of their own. Further investigation evoked a fairly high interest in the possibilities offered by the micro-computer. This is evidenced by the fact that ten companies expressed an interest in discussing further the use of a microcomputer based time cost package. Six of these were interested in testing this type of model, as also were two further companies. All of these companies confirmed this interest when contacted. However, they all felt that an in-company test would have to be long term (12 to 18 months). In addition, they did not have a micro computer system currently available and, as the system used for the research could not be used for this purpose, it was not possible to pursue an in-company test series at this point in time. It is, however, the intention to pursue this approach at a later date, for a prolonged period of time. (See further research, Chapter 8).

Only eight companies replied to Question 4.3 relating to the reasons for not operating a formal system for relating time and cost. The major factor cited was a lack of suitable computer software. Hardware was not seen as a particular problem, a factor that would appear to be due, in the main, to the misunderstanding of Question 4.1a referred to earlier. Further investigation indicated quite clearly that "on site" computer time was largely out of the question as far as large centralised computers were concerned. The cost involved in staff and computer time was considered to be prohibitive. The general feeling (the replies are too few in number to form a definite conclusion), on further investigation is that while there is a general resistance to the concept of attempting to optimise the time and cost relationship this is based more on a lack of understanding of the concept rather than reliable evidence. In fact, face to face discussion, when the underlying objectives could be explained, usually resulted in an acceptance of the potential advantages.

Where further investigation is mentioned above, this refers to either direct discussions or telephone conversations, where appropriate, with those companies who supplied their name with their reply to the Questionnaire.



In addition, many of the factors arising from the Questionnaire were raised with the six sample companies selected for special study, referred to earlier in the chapter and are brought out in greater detail in appropriate sections of the thesis.

The picture emerging from these investigations is one of intuitive decision making situations based mainly on experience in an environment of uncertainty. Many aspects of the problem relate to the time and cost parameters both of which can be quantified and modelled. There is no apparent lack of suitable data for this purpose. Little or no attempt has been made in the representative sample of companies consulted to seek an optimal or near optimal solution to the time cost relationship. While it is possible to convince construction management of the value of doing so as a basis for certain aspects of decision making, they point to two basic reasons as to why this is not a feasible proposition, i) the lack of a suitable, relatively uncomplicated model to analyse and present concise and relevant information as a basis for decision making; ii) given a solution to (i) the need for other than manual methods of computation and analysis, i.e. the use of computers, with the consequent problems of high cost and the ingrained resistance to computer usage, particularly at site level. Accepting assumption (i) and it is clear from these consultations that this assumption is a reasonable one, it is the intention in this research, through the attainment of the objectives set out on page 15, a) to develop appropriate models and b) investigate the potential of the micro computer/s to satisfy the need for high levels of computation and analysis and overcome the problems of high cost and user resistance.

It is interesting at this stage to reflect on the observations made by Popescu<sup>5</sup>, in a paper on the pitfalls of general services (construction) software in the USA where he states that "to have a unique language and tool for planning, scheduling and control at low acquisition cost that is easy to maintain and to be adapted to users needs is still a dream for construction managers". He goes on to say that "the construction industry is in need of a good CPM project management and control package accessible to all contractors and educators to use and to maintain at a low cost".

In summary, it could be said that what is required is a system that is easy to maintain and easy and economical to use, in other words, a system that construction management "have only to learn how to handle and where and when to apply" (Popescu<sup>5</sup>). This may well be an over simplification and may not be fully achievable as far as this research is concerned but it

does equate with the over-riding views of a large body of managers, particularly those with responsibility for decisions at site level.

The time cost parameters and the problem of optimising their relationship investigated in this research, are seen as being central to the problem of planning and controlling construction projects. The production of models capable of analysing this problem is seen as a major step in the evaluation of the "good CPM project and control package" envisaged by Popescu.<sup>5</sup>

## CHAPTER 2. DECISION MAKING

### 2.1 Introduction

This chapter is introductory in nature and is concerned, in conjunction with Chapter 3, with providing a conceptual basis for the more specific aspects of the research.

The first part provides a general definition of the construction industry, highlighting factors that influence decision making.

The second part is concerned initially with general aspects of management decisions and examines some accepted decision theories. It concludes, by identifying the major decision makers and major decision areas, looking briefly at the basic decisions involved in the planning and control of time and cost.

### 2.2 The Construction Industry

The construction industry embraces building, civil engineering and large mechanical plant installations, all three often occurring in an individual contract, eg. a chemical plant with a related range of buildings and roads. The financial value of contracts can vary from as little as a few hundred pounds for small domestic extensions to multi-million pound installations for manufacturing, generating and other large industrial undertakings.

The construction industry also covers a wide range of practical and professional skills. These skills are usually subdivided between design and production. The design is usually undertaken prior to the appointment of a contractor (and therefore without consultation), whose job it is to translate the design into a finished building. Design skills include the functions of architecture, engineering and surveying. These skills are often duplicated on the production side and, in addition, there is a requirement for additional functions such as planning, estimating and a wide range of management skills. The situation is further complicated by the fact that a construction project involves a large number of independent organisation, (sub contractors).

This type of fragmentation is a feature of the construction industry and influences, to a large extent, the way in which it operates. A further distinguishing feature of the industry is the fact that virtually all construction projects are unique, in that with the exception of repetitive

housing, most projects are of the "one-off" type. The role and method of operation of the construction industry therefore differs quite substantially from that of most other major industries.

There are many excellent references available describing in detail, the above, and the many other complex features of the construction industry. It is not, therefore, in this research, the intention to duplicate these works or reproduce the many statistics available. It is felt, however, that the following broad statistics will be useful in giving an appreciation of the size and importance of the construction industry.

- i. The construction industry employs approximately six per cent of the working population.
- ii. The industry annually accounts for approximately 12.5% of the annual gross national product.
- iii. The construction industry is composed of approximately 88,000 firms.

Total employment	Number of firms	% of firms	% of work done
0-1	28 131	32.0	1.3
2-24	53 262	60.5	21.0
25-114	5 391	6.1	20.8
115-1199	1 162	1.3	34.4
1200 and over	71	0.1	22.5
Total	88 017	100.0	100.0

Source : Private Contractors' Construction Census, 1975, DOE.

#### Size Distribution of Firms - October 1973

It can be seen that the construction industry accounts for a significant proportion of the gross national product. It is composed of a large number of firms (92% of firms employ less than 25 people) and provides employment for a high proportion of the working population (1,169,100 - Oct 1975). Harper<sup>6</sup> in describing "The Traditional Building Scene" states that "... we still in the main, bolster up an organisational structure in which the contractor is usually obliged to adopt ill founded time and financial programmes, to erect a project untried and untested by model or simulated studies .... The power of decision is nearly always spread over several different interests and is remote from the scene of operations".

The industry has been used by successive governments as an economic regulator. (Approximately 50% of the capital investment in construction is government financed), a factor which accounts, to an extent, for the high level of liquidations and bankruptcies registered each year. In the context of this research, the writer believes that apart from the economic vulnerability of the construction industry, many contracting failures result directly

from the subjective base on which management decisions are undertaken. This is exacerbated by the competitive bidding market in which the construction industry operates, which increases uncertainty in relation to workload, production and profitability, all of which are further amplified by the less than deterministic environment which usually surrounds the construction project itself.

The construction industry is therefore often criticised for "poor management". Poor management presumably refers to the less than optimal use of resources, inadequate planning and an inability to determine accurately, project costs and establish their relationship with project duration. This applies equally to the pre-tender and operational stages of a contract.

As a result of discussions with the sample firms and analysis of the questionnaires distributed (see Chapter 1), the scale of operation diversity and the versatility of construction firms were not considered to be significant factors in the context of this research. It is also considered that the research is applicable to all but the very small contractors in both the civil engineering, and building, branches of the construction industry. No attempt has been made, therefore, to classify firms on the basis of assets, job size, number of employees, etc.

To fulfil their role, all construction companies require the major production resources of men, plant, material and capital. This applies to even the smallest contracts. Many contracts are characterised by major resource constraints, e.g. major civil engineering contracts depend on availability of plant - work on major road contracts is limited to those firms who already have or can obtain the appropriate plant. Equally, the availability of skilled operatives in particular parts of the country can also constitute a major constraint on building contracts. It can be said, in general, that civil engineering contracts require the use of large, expensive and specialised plant, whereas building construction work is usually labour intensive, although increased mechanisation is desirable. However, the high cost of both labour and plant highlights the need to reduce indirect costs by reducing the time taken in completing construction work.

It was apparent, from discussions with the sample companies, that they all adopted the same general procedure in the preparation of cost estimates. Variances in estimates are due, in the main, to such factors as the availability of specialist plant, the need to keep skilled operatives employed, involvement in prestigious contracts or a failure to appreciate the relationship that exists between time and cost. The overall picture, however, is of a market with a large number of competitors with relatively minor cost estimate differences - a factor reflected in the final tender bid. The competitive construction process can be defined as follows: clients' needs, clients' brief, design, Bill of Quantities or equivalent, selection of contractor/s, and construction.

Expanding briefly on these facets of the construction process, the client having determined the need for a building or other structure, contacts an architect or consulting engineer or in some cases the contractor, direct. A brief is then drawn up outlining the client's requirements. The detail included in the brief varies considerably and may be nothing more than a set of unrecorded ideas. Occasionally it may be defined in very great detail. Once the brief is prepared and agreed, specialist designers are employed to undertake the detailed design work for the building or other structure.

On the basis of the design, a Bill of Quantities or its equivalent is prepared, often from incomplete contractual drawings, or purely on sketch plans. The Bill of Quantities constitutes a detailed description of the material required in the operations to be carried out by the contractor and is normally prepared in accordance with a Standard Method of Measurement<sup>7</sup>. Contractors are then selected and this selection procedure operates in many different ways, most frequently as a form of competitive bidding based on the Bill of Quantities or the design drawings and specifications, or both. In certain cases the contract is awarded by direct negotiation with one or two selected companies, although this is the exception rather than the rule. Certain contracts, mainly housing, are built speculatively, while others are operated on a design/build basis, whereby the contractor is responsible not only for the construction but also the design procedures. Finally, once the contractor has been selected, the work

is completed in accordance with the plans and specifications and other forms of contract instructions. This research project is concerned with the natural decisions taken at virtually all stages of this process. A report prepared by the Building Economic Research Unit<sup>8</sup> reviewed the reasons underlying the decision to tender by construction contractors. These were identified as follows:

	<u>%</u>	
Type of work	26	
Location of work	27	
Size of work	27	Features of Contract
Designer in charge	9	determining the Decisions
Client	8	to tender.
Others	3	
	<u>100%</u>	

Generally speaking, a situation of uncertainty arises at the stage at which the tender is actually submitted in that the contractor is unsure of the likelihood of the success of his bid. It was considered initially that this aspect might be significant in terms of this research project and consideration was given to the first attempts to model this situation by Friedman<sup>9</sup>. Later models presented by Rickwood/Curtess and Main were also studied. It was concluded however that these models were not related to the problem of modelling optimum relationships between time and cost, and no further consideration will be given in this research project to to modelling aspects of bidding strategy.

It was the unanimous view of the sample companies that competitive bidding is very much a lottery and although they agreed that the success ratio might well be improved by a more objective approach to time, cost and their interrelationship, nevertheless there was a strong feeling that it is the inherent uncertainty of the situation that ultimately defines success. With one exception, time cost relationships were ignored and having arrived at a "gross cost", the "mark up" was identified as the ultimate factor in determining the final tender bid. Ruby and Milner<sup>10</sup> state that "It is partly the process of awarding contracts to the lowest bidder that accounts for construction contracting having among the lowest profit margins of all industries, often as low as one per cent."

There appears to be little likelihood of a move away from this form of competitive tendering. One of the most intensive surveys of the construction industry is described in the Banwell Report<sup>11</sup> which states that "many clients consider that a building can only be secured at the lowest possible cost if each job is advertised and all contractors are free to quote a price in competition". It is considered that this attitude is still the prevalent one in the construction industry.

This element of uncertainty in relation to the success of the initial bid continues throughout the life of a construction project and is further exacerbated by the large number of variations from the original specification (it is not unusual for a 1000 or more variation orders to be issued on a contract) often required by the client. Estimating uncertainty generally is caused by information gaps and the subjective nature of the estimating procedure.

It is useful at this point to differentiate between estimating and tendering. The definition used in this research is that suggested in the Chartered Institute of Building's "Code of Estimating Practice"<sup>12</sup> which describes estimating as "the technical process of predicting the cost of construction and tendering as the separate and subsequent commercial function based upon the estimate", Adjudication is the term used to describe the action taken by management to convert an estimate into a tender. There are, therefore, two major decisions involved:-

- i. The decision to tender for a particular contract.
- ii. The value of the final tender figure.

These decisions will be based on a preliminary examination of a specific contract and consideration of the company position and market environment.

The Code of Estimating Practice suggests that "estimating should be an explicit and consistent analysis of the methods of construction" and that "it is believed that such a sound estimate can only be achieved when each operation is analysed into its simplest elements and the cost estimated methodically on the basis of factual information". This implies detailed planning of time and cost but does not mention their inter-relationship. It also ignores the fact that the Bill of Quantities on which the estimate is usually based has been described as a "hypothetical construct"<sup>13</sup> (Higgins & Jessop). This definition of the Bill of Quantities was considered "particularly appropriate" by the sample construction companies given that the design is very rarely completed at the time when the Bill of Quantities is prepared.



Many important working drawings are not completed until construction is well under way and, in some cases, not at all. As the Bill of Quantities is rarely prepared from completed drawings and specification it is inevitable that it will contain a large number of provisional and "guess" items. It is apparent therefore that the contractor is not preparing an estimate for a precisely defined design and method of construction but is, in fact, competing for the opportunity to construct what is little more than a hypothetical building. A further significant factor is the time allowed to prepare the tender - often as little as 2 weeks, rarely longer than 4 weeks. Bearing in mind the complexity of many construction projects, this leaves little opportunity for the planner to investigate alternative methods of construction. In the majority of cases, a considerable period of time elapses between the submission of tenders and the actual award of the contract. This represents a further period of indecision and uncertainty in which it is impossible for the contractor to allocate and balance scarce resources between individual contracts.

Generally speaking, the Bill of Quantities does not identify specific methods of construction although this must be attempted in preparing the estimate. An instance was quoted by one of the sample companies where the architect had, in fact, designed the building with a particular construction method in mind. This, however, "was not communicated to the tenderers and only came to light after the contract had been awarded". Harper<sup>6</sup> suggests that "The named signatories to a building contract (client and builder), should spend much more time matching design to building resources ...." It would be logical to expect that this type of problem would disappear once the contract was actually awarded. However, again it was apparent from discussions with sample companies, although they were in many ways reluctant to admit this, that there is often little contact at the estimating stage between the potential contract managers, the planners and estimators. Equally, when the contract is actually under way the basis of the estimate was rarely communicated to the construction site, in fact in many instances the estimator never actually visited the contract at all during the construction period. From the foregoing, it can be seen that there is a complete lack of correlation between the hypothetical structure described in the Bill of Quantities and the other tender documents and the final structure itself. In this situation a high level of uncertainty is inevitable.

Construction uncertainty during the process of the contract is caused by a wide variety of factors (see Chapters 3 and 4), in addition to those already mentioned. It is suggested in this research that an additional factor of major significance is the lack of an objective facility for predictive decision making.

### 2.3 Management Decisions

Management decisions are concerned with the interaction of the information available to the decision taker and the decision he takes. By formulating decision criteria this theory constrains the executive to consider explicitly the purpose of the decision and enables him to take into account all relevant information and arrive at the correct decision. This may appear a far too sweeping claim but it must be remembered that decision theory is only a means by which the decision taker can do his work. It is no substitute for his expertise. It will not remove guesswork altogether, but confine it to areas where no better knowledge exists; it highlights the cost of lack of information and hence allows the cost of collecting more information to be weighted against the value to be gained from it.

Decision making, although one of the principal aspects of the manager's job, is one in which he is frequently faced with uncertainties. In such cases, the decision maker must base his deliberations concerning outcome possibilities on subjective opinion and the subsequent decisions become predictive in nature. Predictive decision making is widely practised in the construction industry and highly expensive resources are often committed in this way. The efficiency of this commitment cannot be ascertained unless the accuracy of the decisions can be determined. Given a satisfactory method of measuring and evaluating predictive decisions it is apparent that the objective nature of the information should be as accurate as possible to ensure effective analysis. Note must also be taken of individual behavioural traits in terms of possible variations that exist between optimistic and pessimistic predictors. There may also be differences between the predictive decisions of particular groups of specialists i.e. site managers and planners. In practice it is considered that planners can predict accurately over longer time scales than can site managers. Figures quoted suggest time scales of 2 - 5 weeks and 1 - 3 weeks before the occurrence for planners and site managers respectively. Evidence suggests that predictive accuracy of site personnel over long periods tends to be poor and erratic, although in the short term, say a maximum of three weeks from the event, results are very much improved. In most cases results are best for activities which the predictor regards as critical and for which he has immediate responsibility.

It is also likely that the accuracy of predictions will vary with the type of work being undertaken on any particular site.

The magnitude of a decision at a specific level will normally be judged in terms of the resource commitment its implementation will require and the risk factors associated with this commitment in relation to the expected outcome. As the level of management becomes higher the accent on decisions of greater magnitude increases. Jacques<sup>14</sup> describes this phenomenon as the 'time span of discretion', suggesting that "each manager has the discretion to make certain decisions and that it is the time period between their implementation and the resulting outcome which determines the responsibility that a manager bears in his job". Higher management tends to have a longer time span of discretion than lower management, thus their decision making is, perhaps, more important. It is as well to remember however, that all managerial personnel are given some discretion, all make decisions, and by doing so all contribute to the well being or otherwise of the organisation they serve. An improvement in this function at any level can provide only benefit, both to the individual and the corporate body.

Decisions, once made, commit a company's resources. Accurate decisions where actual outcomes are as predicted will encourage efficient use of these resources, inaccurate ones obviously result in waste. However, without a method of evaluating a decision there can be no check on this and the firm may well be sustaining unnecessary losses of which it is totally unaware.

In the construction industry there is often a conflict in management between the entrepreneur who traditionally makes his decisions on the basis of intuition and experience, and the technologist who seeks a deterministic solution to the problem, that will hopefully provide the one correct answer. However, given that managers will always wish to arrive at a rational decision, the answer often lies in combining the intuition of the entrepreneur with the analytical ability of the technologist. The objective being to provide a quantitative basis for taking decision where problems occur in conditions of uncertainty. It is appropriate at this point to distinguish between certainty and uncertainty in that decision making can take place under either of these conditions.

Decisions under Certainty - Possession of objective information concerning all the variables connected with a certain problem should generally result in an accurate decision. The return to be expected from each alternative strategy developed for solving the problem must be determined and then the decision taken as to the strategy that gives the highest return in terms of the original objectives. The main task will be in calculating possible

outcomes from the information available. These outcomes should be sufficiently accurate to allow for effective comparison. In the context of this research, the term certainty is not taken to imply a precise knowledge of all the factors relevant to the situation. It does mean however that they are sufficiently well known to allow a high level of confidence to be placed in accuracy.

Decisions under Uncertainty - In most situations full objective information is rarely available and uncertainties will exist. This is more often than not the case in the construction industry, particularly when no accurate means of analysis is available. This applies in particular, in this research programme where the relationship between time and cost is being considered. When uncertainties exist, as they invariably do, and there is an absence of objective information, the manager will naturally draw upon his experience or judgement. This general lack of objective information and methods of analysis has often resulted in construction managers placing too much faith in subjective decision making when dealing with uncertain conditions. It is not, in fact, unusual for decisions to be made on an intuitive basis, even when full objective knowledge suggesting a contrary course of action is available. Many managers would argue that a subjective element exists in all decision making situations. In support of this Sanders<sup>15</sup>, states that "objective technique provides a probability reference point which the forecaster sharpens by critical appraisal with the use of additional subjective information. There are no objective decisions which cannot be improved upon by the forecaster in this way, even when the objective method produces results which are superior to the objective forecast made before its introduction".

It could be argued that in the construction industry nothing is totally predictable therefore the concept of certainty is totally unrealistic. It is important to realise however, that we are not concerned with problem areas where it is possible to predict exactly the outcome, but with activities where we can forecast with some considerable confidence what is likely to happen. For example, it is necessary to forecast reasonably accurately the cost of a particular activity on a construction site, without being exactly sure of the final cost. Decision theory does attempt to quantify uncertainty through the concept of probability. This is not simply a descriptive term that indicates whether an event is highly probable or improbable but is a measure of the real likelihood of its occurrence.

Most construction problems require consideration of a combination of separate activities each of which have their own distinct probabilities. Furthermore, different combinations may apply, for instance, in a planning situation, different probabilities are combined to determine the project completion date. However, because of the number of activities involved and the fact that each separate activity that makes up the total project network will have a probability distribution between two extreme limits, i.e. a shortest possible duration and a longest possible duration, we can only determine the most likely project completion date. The practical value of probability theory in relation to activity duration is discussed further in Chapter 3.

A further factor that must be taken into account is variability. Statistical variations and variants are specific terms with very precise meanings and in the context of this research it is important to note that many problems do not have a consistent answer. It is also important to note that when all the inputs to a system appear to be constant the output may still vary. What must be accepted is that variability does occur and furthermore that it may be possible to measure it.

The concept of risk which refers to the chance of unacceptable losses arising at some point in time is obviously also very relevant to the construction industry. Risk which is most frequently associated with cost, will be viewed in different ways by different organisations. Where cost is the factor at risk the attitude will obviously be influenced by the amount at risk. The amount of profit likely to accrue from risk taking will also have a significant effect on the decision maker. There are other factors that may relate to risk such as contract duration, decisions to tender, client attitudes etc. The decision maker will be required in a situation of risk to evaluate alternative courses of action. Irrespective of the nature of the risk the objective should be to base decisions on as much quantitative information as possible.

Simon breaks down the decision process into three phases, viz:

- i. the intelligence activity - searching the environment for conditions calling for a decision
- ii. the design activity - inventing, developing and analysing possible courses of action
- iii. the choice activity - selecting a course of action from the alternatives

emphasising the fact that each phase is itself a complex decision making process.

In most industrial situations decisions are made by managers in an attempt to achieve certain specific objectives within the constraints set by the overall aims of the organisation as a whole. These overall aims will, of course, have an over-riding effect on the intelligence activity described above.

The choice activity allows freedom or discretion to accept or reject any possible outcome, to pick one as being the best and to commit resources to its achievement. It could be argued that this is the most important decision making phase, however the ultimate choice of the most suitable course of action is only possible when alternative courses of action have been identified and analysed. It is in the design and analysis activity that most of the manager's decision making skills will be exercised. These skills will include many different attributes, not least of which will be those of comprehension and reason, but all will be only facets of a main requirement - the ability to obtain, develop and use to advantage, information in whatever form it manifests itself.

The making and implementation of decisions is therefore the means by which a manager seeks to achieve specific objectives. However the ingredients on which decisions are based are the types of information available. Ross<sup>16</sup>, in dealing with information systems states that "an organisation simply cannot survive without the critical element of information nor can the functions of management be performed unless a flow of information is provided to decision makers". This is particularly true of information relating to time and cost. Ross concludes "The task is to upgrade many of these systems from the historical variety to the type of specific application that will provide better decisions and information for planning and control". Examination of a decision/information system within a company will show that the two are inextricably linked.

Company objectives are a set of decisions taken by top management relating to the future aims of the organisation. In setting these, information concerning the internal resources and potential of the company and the external environment must be considered. Once set they are devolved to the various departmental/site managers - where they become information which these people can use in formulating their own decisions. These are further devolved to their subordinates who use them as information for their decisions, and so on down through the organisation.

A similar process takes place in the opposite direction, where decisions made by an operative on site produce certain results which are fed back up through the hierarchy, thus providing information which management will use in making further decisions. The process also works laterally. In this way the whole organisation becomes involved. Once a decision has been made it can be communicated in any direction to other people and when received becomes information which the recipient may use in his own decision making process.

The quality of decisions made will be affected by the availability and ease of access to information, its accuracy and pertinence to the problem, and the skill and judgement of the manager in using it.

Information can be classed into two principal types - Objective and Subjective. Objective information is that which is factual and related directly and truthfully to the object in question. In the context of this research it is information that is generally verifiable within a framework of mathematical, and scientific rules. It is 'hard' information and is completely divorced from the opinion, judgement or intuition of the individual.

Subjective information is that which exists within the mind of the individual and relates to, or reflects his thoughts or feelings. In an industrial sense it is based upon the knowledge, experience, intuition and judgement of the individual and as such is 'soft' in nature and difficult to quantify.

If all information were purely objective, decision making would be a much simpler process. However, in practice and particularly in the construction industry this is not the case and there is always a high element of subjective information. As with the majority of things in the industrial world there is very little black or white but mostly varying shades of grey.

Attempts have been made to measure and evaluate the accuracy of subjective decision making, and the likely effect upon company performance, productivity, and profitability. It is quite clear that the accuracy of subjective decision making will vary from individual to individual. It is obviously advantageous to keep this element of decision making to a minimum and replace it wherever possible, with decisions based on objective information.

It is apparent from studies carried out during this research programme that the length of the period to which a decision relates is of considerable significance. This is due, in part, to the fact that objective information is usually more readily available for short term decision making.

Nevertheless, the need for quick decisions may still create a situation whereby objective data is disregarded or left unanalysed due to lack of time. The ability to analyse objective data rapidly is therefore of paramount importance. It is usually impractical or impossible to do this manually, hence the emphasis in this research on the use of on-site micro computers.

It is extremely difficult to instigate control procedures where a high percentage of decisions are subjective in nature. It is generally too late to judge the effectiveness or otherwise of a decision when an activity or project is complete. This is particularly true in an industry where risk and uncertainty are, to an extent, inevitable. The manager's aim should, therefore, be to seek optimum solution or near optimum, based on objective data or information wherever possible. Many well informed people in the industry hold the view that this is impossible and argue the case that subjective decision making is acceptable due to the high level of uncertainty.

Numerous attempts have been made to quantify the balance between objective and subjective decision making and these have produced a whole range of, what might be termed as quasi objective decision making techniques i.e. work measurement.

The development of objective and quasi-objective information can be very costly as it must be up to date and relevant to a particular situation. It can be argued that information, once developed, is available for all time and can therefore be used again and again. Ross<sup>16</sup> accepts that this may be so but adds "information should only be re-used if it is accurate within the tolerances required by the new problem and is in context with it. It must, therefore, be accepted that there are certain limitations associated with objective information". Accepting these limitations, what is essential is that the manager can base his analysis on models that are effective regardless of variances in information.

It would appear from this study that there is, in fact, no lack of objective information in the construction industry. What is really missing is a quick and accurate method of analysis that enables alternative solutions to be compared, using criteria such as time and cost. This applies not only to planning and the search for an optimum solution but equally to controlling and revising the plan as factors such as resource availability change. In this way the time scale between the decision and its implementation can be kept to a minimum thus increasing its potential accuracy. This is not to say that subjective decision making can or should be eliminated. The two factors are complimentary and together will increase the decision making skills of the manager.



## 2.4 Decision Theory

Management decisions were discussed in Section 2.3. It is useful now to look briefly at established decision theory. A number of alternative decision theories have evolved over the years, each focusing on different aspects of the decision itself and the process by which it is reached. These theories can be classified according to one or more dimensions, such as descriptive/normative, satisficing/optimizing, and individual decision making/group decision making. These are rather crude dimensions and it is considered more appropriate to adopt the classifications suggested by MacCrimmon<sup>17</sup>, i.e. choice theories and process theories. Choice theories are concerned with the choice itself and procedures for reaching optimal solutions, whereas process theories focus on the process that precedes the choice, with the solution being some satisfactory by-product of the decision process. We can also say that, in general, choice theories are normative whereas process theories are descriptive.

Process Theories - are concerned primarily with the individual's ability to adjust to decision situations. The decision maker is assumed to have aspirations in a number of dimensions. When aspirations in a certain dimension are not achieved new alternatives will be sought. These are generated sequentially until the aspiration level is reached. If the search is not successful the aspiration level may well be lowered. If it is easily and rapidly achieved the opposite may be the case. Typically the search considers only one dimension at a time and elements of uncertainty will be avoided where possible.

This brief summary is used to highlight only what are considered to be the most important elements of process theories. Lindblom<sup>18</sup>, March and Simon<sup>19</sup> and Cyert and March<sup>20</sup> describe these theories in detail and provide numerous examples based, mainly, on findings from empirical studies on organizational decision making.

Choice Theories - are concerned with achieving optimal decisions in a given situation. The choice is therefore the essential part of the process. The decision maker is assumed to have to choose between a set of finite or infinite alternative courses of action. The consequence of a particular choice depends on which of a set of events will occur.

Decision situations are characterised as being made under certainty risk or uncertainty (pp 24, 25 & 26). Certainty assumes that a known set of events will occur. The events can then be ranked according to the consequences and the optimal alternative is the one having the best consequence. Optimal decision techniques include traditional production and financial analysis extending into the more mathematically precise techniques of dynamic and mathematical programming. As stated earlier in the section (pp 24 & 25) certainty in the context of this research does not imply a precise knowledge of all the factors relevant to a given situation.

In risk situations it is not known which event will occur but a probability distribution can be assigned to the set of events.<sup>21</sup> Decision situations under uncertainty cover all other cases. Knight states that "The practical difference between the two categories, risk and uncertainty, is that in the former the distribution of the outcome... is known ..., while in the case of uncertainty this is not true, ...". This division into risk and uncertainty depends on the interpretation of the probability concept but the probabilities are generally assumed to have an "objective" basis. Knight also states that "We can also employ the terms 'objective' and 'subjective' probability to designate the risk and uncertainty respectively..." A consequence of the personalistic interpretation of the probability concept is therefore, that for the purpose of this research, there is no reason to distinguish between risk and uncertainty since a probability distribution can be assigned in either case. Although the central theme of this research relates to the development of an objective basis for decision making it is nevertheless accepted that the final decision will contain a high level of subjectivity.

Decision Analysis - is defined by Howard<sup>22</sup> as "a logical procedure for the balancing of the factors that influence a decision. The procedure incorporates uncertainties, values, and preference in a basic structure that models the situation." and is often considered to be synonymous with Bayesian decision theory (Raiffa<sup>23</sup> ).

The Decision Analysis Cycle as described by Howard<sup>22</sup> is shown in Figure 2.1.

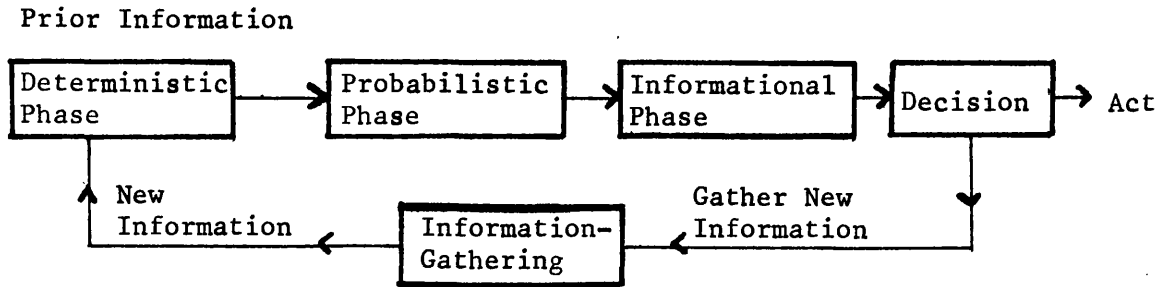


Figure 2.1

**Deterministic Phase** - In the deterministic phase the first step involves defining and bounding the decision problem followed by the identification of the alternatives. The relevant state variables are then defined, i.e. time scale and cost of production, demand for the product, eg. speculative housing. The consequences of choosing the different alternatives depend on the values of the state variables. This relation is described by a structural model. This model has the consequences as its output.

The next stage involves evaluating these consequences e.g a measure of profit.

The deterministic phase is concluded by a sensitivity analysis. The state variables are assigned different values within reasonable range and a study is made as to whether the variables affect the results of the different alternatives. Sometimes it is found that certain alternatives are dominated, i.e. they are inferior to other alternatives regardless of the values of the state variables. The sensitivity analysis also shows where uncertainty is important.

**Probabilistic Phase** - This phase has been discussed earlier and is again considered in Chapter 3 and is not therefore given further consideration at this stage.

**Informational Phase** - The informational phase begins by measuring the expected value of perfect information about the state variables, individually and jointly. This represents the maximum value of any kind of information. One of the most important features of decision analysis is that it shows the impact of uncertainties on utility or profit. The next step is to determine the value of feasible information gathering programs.

A decision then has to be made as to whether to act according to the best alternative or to gather more information.

It could be argued that major decisions in the sample construction companies are made in a similar fashion. However, there are certain features of decision analysis eg. time cost optimisation, that will hardly ever be found in the traditional analysis of decision problems and risk preferences are generally handled intuitively rather than explicitly as part of the analysis. Finally, the evaluation of information gathering alternatives in order to reduce uncertainties cannot be made without the preceding steps of decision analysis.

#### Advantages and Disadvantages of Decision Analysis

The incremental advantage to be gained from the whole decision analysis approach could be offset by the effort, time, and cost of the analysis. This means that the application of decision analysis should be restricted to major problem areas e.g. a significant proportion of the organization's resources would be involved where the problem has a complex structure with many interacting factors affecting the decision, or the organization may be affected by the results of the decision for a prolonged period of time.

Howard<sup>22</sup> draws the distinction between a good decision and a good outcome as follows:

"A good decision is a logical decision -- one based upon the uncertainties, values, and preference of the decision maker. A good outcome is one that is profitable, or otherwise highly valued. ...., we find no better alternative in the pursuit of good outcomes than to make good decisions".

In that decision problems are often complex, a systematic approach will force the decision maker to quantitatively formulate the interactions of various aspects of the problem.. This type of analysis makes it easier to study the sensitivity of the decision to changes in assumptions and judgements.

An argument frequently used in the approach to subjective decision making is that people are often inconsistent in their probability assessments. However, Schlaifer<sup>24</sup> puts forward the following counter argument:

"The fact that a decision maker's initial judgements about chances are frequently inconsistent is one of the strongest reasons for assessing explicit probabilities, since this is the only way in which the decision

maker can make sure that his inconsistencies will be detected and corrected before they have had a chance to lead to a defective analysis of his decision problem".

A formal analysis and presentation will make it easier for the recipients to understand the underlying basis for the decision. It will highlight factors that have been omitted as well as those included. It will generate feedback for future decisions.

Different parts of analysis can be isolated for treatment in different places in the organization when a problem is well structured, i.e. estimators, planners. Decision analysis provides a common language and facilitates communication about uncertainties and values. The decision maker will, however, still have control over the different phases of the analysis and understand the inter-relationship between the judgements.

A systematic examination of the value of information highlights the need to search, gather, compile, and organise data from new sources.

The decision maker will have to distinguish between preferences for consequences on one hand and judgements about uncertainties on the other. It can be easy to overestimate the probability for an "unlikely" event.

It is not unnatural that different people can reach different decisions with respect to a certain problem. By breaking down the problem into its basic parts it is possible to identify the major part of the decision complex and isolate points on which there is fundamental disagreement. Attention can then be concentrated on these points i.e. management by exception.

It is relatively easy to incorporate new information into the decision situation. The structure of the problem will often remain essentially the same if, for instance, an assessment has to be changed. The computer programmes designed as part of this research (Chapter 6), mean that it is easy to analyse a problem of a given structure for different sets of inputs.

The formal analysis of the problem will provide historical documentation of the decision that has been adopted. This might prove valuable in coping with staff changes and in briefing new parties to the decision making process.

## Disadvantages

It is essential that discretion be used when setting up a quantitative model to reduce unnecessary complexity. This is where the experience and subjective skills of the planner are essential

The judgement of risk is often a variable factor, depending on the personal characteristics of the decision maker. It is essential therefore that an overall risk policy is set at the highest level i.e. Board of Directors, that can be communicated throughout the organization. However, decisions are made at all levels, often without a clear understanding of company policy. In many cases site managers who are directly accountable for production levels may be extremely reluctant to make decisions that involve a high level of risk. This can apply even if the decision has a high probability of producing a successful outcome.

In a construction company certain goals have to be reached e.g. turnover, level of production, maintaining the size of the labour force, etc. These restrictions are taken care of in the deterministic phase of the decision analysis. Alternatives whose consequences do not fulfil such constraints are not feasible and are eliminated. In most cases, however, these will not be absolute. For example, a large enough increase in long-term profit should offset a small reduction in market share.

It can be said that the formal way of attacking decision problems does not take into consideration limitations or oppositions that might arise in the environment. The former, however, should be taken care of in the deterministic phase since this should only contain feasible sequences. An antagonistic environment could probably be accounted for by assessing probabilities for different events. These probabilities could sometimes be derived with the help of game theoretic models.

One aim of decision analysis is to structure a complex problem into smaller problems so that attention can be focused on one small part at a time, e.g. an activity or sub-activity. Experts are being asked elemental, clear (and sometimes hypothetical) questions instead of complicated ones. The trouble is that these simple questions can be more difficult to answer, perhaps because experts are seldom used to considering simple problems. It could also be difficult for an expert to disclose his choice in simple situations.

It is considered therefore that the only serious disadvantages relate to the scaling of judgements and preferences (single or multiattribute), but these difficulties can be reduced as the techniques are further developed and become more generally accepted. In conclusion, it is suggested that these disadvantages are more than offset by the advantages to be gained from the use of formal decision analysis.

## 2.5 The Major Stages of Decision Making in the Construction Industry

The main thrust of this research is concerned with quantitative decision making, particularly the use of mathematical models. Mathematical models are used as a basis for decision making in a wide range of human endeavour. However, the application is very much in its infancy and lagging well behind the development of theoretical models.

Bjornsson<sup>3</sup> in examining the reason for the current limited use of quantitative techniques in construction projects states that "... misconception may be primarily routed in the way the techniques have been marketed by the researchers working within various applied scientific disciplines... The area of operations research is turning more and more inward and is talking less and less to the managers who have the real problems. This trend is exemplified by the appearance of papers in the journals of the profession that seem to be a cure searching for a disease ... those who argue for the extended use of advanced analytical techniques in construction management find little support in the literature that is not anything more than total lip-service."

The use of quantitative models introduces an essential feature into the planning and control features of a manager's job, that of precision. It is possible also, having broken down a problem into its basic components, to include certain aspects of experience and judgement as a logical part of the input. This is particularly significant in that rather than constituting the basis of the decision these factors will themselves become facets of the inputs that influence the decision. They will not, therefore, as is generally the case, "decide" the decision on the argument that "this is the way we have done it in the past" (A statement made many times during discussions with the sample companies):

To manage effectively the manager must understand the mathematical model being used in order to understand its limitations. For instance, the model designer can introduce bias into the decision process without the user being aware of its nature or even its presence. It should be understood that any model is an abstraction from reality and therefore simplifies the real worked. The nature of the simplifications should be clearly understood since

it is possible to leave out the relevant variables in order to be able to solve the problem. The task of the construction manager in the future will become much more complex. In the past the decision maker could rely on intuition and imperfect information. This was all that was generally available to him. Given this situation the basis for the decision was not documented and therefore it was not possible to criticise it in a constructive way. This is not the case when sophisticated models are used. The whole basis of the decision is thrown open for discussion, criticism and revision. These models require expert interpretation and the seemingly precise answers can be misleading. Therefore the information they provide will require interpretation before final decisions are made.

Major Decision Areas - Consideration is now given to the major stages of decision making involved in construction projects. There are three clearly identifiable stages viz: the pre-tender stage, the pre-contract stage, i.e. period between the award of a contract and the commencement of site operations, and the contract period itself.

Consideration relates to decisions taken by top management, such as Area Managers, Contract Managers, Site Managers, Planners, Surveyors and Estimators, and therefore excludes routine decisions relating to day to day activities of operatives at site level.

Pre-Tender Stage - At this stage the major role of the management team relates to the identification and sequencing of the major activities that constitute the contract and establishing a duration for each activity and an overall duration for the contract as a whole. The second major activity is concerned with identifying costs associated with each activity in terms of materials, plant and labour and aggregating these costs and establishing overhead and profit margins appropriate to market conditions prior to arriving at a tender figure. Decisions at this stage have to be made in a relatively short time span and are often based on uncertain information. Both time and cost estimates are made to a large extent on information provided in the Bill of Quantities. Information for decision making will be required at short notice on the costs of material, labour, plant, indirect costs and the time scales associated with these factors.

The over-riding objective at this stage, is to arrive at a tender figure and possibly a related overall duration that will secure the contract. In practice it would appear from discussion with the sample companies that in the main, little thought is given at this stage to the future planning and control of the contract, if and when awarded. Nevertheless, an extensive



volume of objective information is required and a range of very significant decisions must be taken. In that the tender figure to be submitted is largely irreversible, in terms of time and cost, this could be considered the most important decision area of all.

It can be argued therefore that objective information on time, cost and method is absolutely essential at the pre tender stage. Nevertheless, in practice decisions are to a large extent, subjective in nature. Little or no attempt is made to relate time and cost or to optimise this relationship, even though both factors may be a requirement of the client's brief and will therefore form the basis on which the award of the tender will be made.

Incorrect decisions made at this stage will not only involve the company in unnecessary costs but it is likely that errors made at the pre-tender stage may be compounded once the contract is actually awarded. It can be seen therefore that the need for objective information and the ability to analyse it quickly and accurately is of considerable significance at this stage and that unsubstantiated subjective decisions taken at this point will have a most significant effect upon the successful and profitable running of the contract if the tender is ultimately successful. Discussions with construction companies described earlier in the research pointed particularly to the subjective nature of decisions relating to the "mark up" figure to be added to the estimate to obtain the final tender figure. Several attempts have been made to model this factor in terms of bidding strategy.

Earlier research on bidding strategy and current practice is centred on arriving at "optimum mark up" that is the markup which in the long term will produce maximum profit. Friedman<sup>9</sup>, Gates<sup>26</sup> and other more recent researchers suggest the use of probability calculations as a means of predicting the overall success ratio, by raising marks up when work is plentiful and reducing the mark up when the market is depressed. Although related, it is not considered that these models are of direct significance to the objectives of this research.

The duration and financial value of a project are however, significant factors in determining the profit rate for that project. Adrian<sup>25</sup> states that "Given two projects of equal financial value but different expected durations the project with the longer duration should have a higher total profit owing to the time value of money and opportunity costs. Similarly, if two projects have equal duration but different financial values the contractor may be willing to accept a lower profit rate for the project with the larger financial value".

The decisions taken by the directors and senior management at this stage on such factors as contract duration, investment and risk, current and future work load, knowledge of competitors, anticipated returns on investment and time cost relationships are largely intuitive. It is accepted that it would be difficult to quantify all of this information, however the overall accuracy of the tender figure would be improved considerably by the availability of an objective method, whereby alternative combinations of information on time and cost could be analysed - speed is essential and this implies the use of a computing facility - and the relationship between these two factors optimised.

Pre Contract Stage - If the company is successful in achieving the contract tendered for, it will be necessary to repeat, in much greater detail, the processes undertaken at the pre tender stage. Once again, it would be necessary to determine activity sequences, identify individual durations for specific activities and for the contract as a whole and the level of appropriate resources for each individual activity. The key resources of manpower, plant and materials must be carefully scheduled to ensure that they do not arrive on the site too early resulting in payment for unproductive time. If they are ordered too early and arrive on site before they are needed the cost will be expended at too early a stage and additional costs may well be incurred in storage and protection. Alternatively, if they are recruited too late the activity will be delayed with a consequent effect on target dates. As at the pre tender stage there will always be an element of subjective decision making. Once again, however, the more objective the information available at this stage and the more flexible the method of analysis, the more likelihood there is of establishing successful planning and control procedures to achieve the specified objectives.

Contract Period - Once the contract is under way, decision making takes on a new significance and the long term implications of the detailed plan must be taken into account. Each section of the detailed plan must be examined in relation to immediate needs, therefore the time scale of decisions is considerably reduced and moves nearer to the periods of accuracy described earlier i.e. 1 - 5 weeks for planners and 1 - 3 weeks for site management. Greater accuracy should therefore be possible and decisions should, to an extent, move towards a more objective state. Each section of the original plan can be examined in detail under what might be described as more certain conditions. Resource availability and the likely time scales and costs can be ascertained with much greater certainty.

It will be necessary, at this stage, to re-assess and analyse the original plan, replacing what is now demonstrably "uncertain" information with something more accurate. Nevertheless, even with the shortened time scale now being considered, objective analysis has proved extremely difficult in practice, due to the complex and variable nature of the range of alternatives available and the need to analyse them quickly and select alternative strategies for decision making.

There will still, however, be the need for subjective, intuitive decision making on the part of site management staff due to such factors as strikes, breakdown of equipment and inclement weather. When this type of interference occurs early reassessment of the situation is required and the analysis process comes into operation once again. In this changed situation the site manager will again have to re-determine activity sequences, judge durations, arrange the delivery programme for material and plant, possibly re-arrange subcontractors and relate the revised time scales to the cost and financial plans for the work in hand to ensure continuity and full utilisation of resources. For instance, men recruited to commence work at a particular time period may be unemployed due to plant failure and will require payment for unproductive time or alternatively, they must therefore be employed in some other form of activity. This, in turn, will affect the sequence of related activities and, of course, the cost and duration.

When an activity commencement decision is changed, a large number of decisions may follow in its wake, all containing elements of uncertainty and often requiring subjective decisions where some method of rapid objective analysis is not available. In Chapter 3, 3.2, the purpose of preparing a short term plan is seen to be that of keeping the master plan alive and responsive in the light of changing or unforeseen circumstances, thus highlighting the need for continuous feedback and updating.

It is at this point in the process that the function of controlling, which is considered to be "inextricably interconnected" with planning, attains major significance (Chapter 3). Control can only be exercised when deviations from the original plan can be readily identified and immediate replanning undertaken. Control, of course, would not be necessary if the construction manager could depend upon the flawless execution of the original plan. However, in practice it is unlikely that performance will ever equate exactly with plan. The current state of decision making on construction sites makes comparison of the plan with actual performance extremely difficult, often impossible. There is no facility for rapidly assessing the effect of changes in relation to the original plan. Planning

and controlling must be seen to be completely interdependent and integrative in nature and must not be viewed as separate functions.

It is useful at this point to identify the major decision areas and the key decision makers involved in the production process and look for links between them. Weinberg<sup>27</sup> defines construction management as "that group of management activities over and above the normal architectural and engineering services related to a construction programme, carried out during the pre design and construction phases, that provide control of time and cost in the construction of a new facility".

This hypothesis is confirmed by other writers and equates with the objectives of this research.

Bearing in mind that the research is concerned primarily with the "production" function as opposed to the "design" function (although many aspects of the models designed are applicable to either), the key decision makers are generally the Directors, Contract Managers, Site Agents, Site Supervisors, Planners, Estimators and Quantity Surveyors. The major decision making stages and the personnel responsible for final decisions at these stages were identified as a result of discussions with the sample companies as follows.

Marketing Stage - Marketing Director, Chief Estimator and Chief Quantity Surveyor.

Pre-tender, Costing and Planning Stage - Estimators and Planners.

Decision on Tender Figure - Directors and Chief Estimator/Quantity Surveyor.

Detailed Planning Stage - Contracts Manager, Site Agent and Planners.

Surprisingly, Estimators were rarely consulted at this stage.

Construction Stage - Contracts Manager, Site Agents, Planners, (although not always), and a range of Supervisors/Engineers responsible for various site activities.

Although it was quite obvious that decisions made at these various stages were interrelated and influenced one another, there was little evidence of formal coordination. The lack of information and the time to analyse it effectively prior to making decisions was quoted as a major problem. A problem that applied not only to design decisions over which the contractor has no influence, i.e. external sources, but to internal decisions within the organisation itself.

The main decisions relating to the time and cost parameters relate to such factors as:

Time

- i. Working sequence
- ii. Resource levels and constraints - labour, plant, materials and finance
- iii. Duration of individual activities
- iv. Earliest and latest starting dates for individual activities
- v. Interrelationship between activities
- vi. Critical activities - management by exception
- vii. Target dates for individual phases and the contract as a whole.

Cost

- i. Direct costs of materials, manpower and plant
- ii. Direct Costs - Minimum, intermediate and crash costs. Data on other than minimum or what were described as "target costs" is rarely available.
- iii. Indirect costs under specific expenditure headings.
- iv. Cash flows and the effect of deviations from cash flows.

The significance of these factors is developed in greater detail in Chapters 3 and 4.

## CHAPTER 3. PLANNING AND CONTROL

### 3.1 Introduction

The first part of this chapter examines the functions of planning and control, developing the hypothesis that these two functions are "inextricably interconnected".

Sections 2 and 3 examine the characteristics of the time and cost parameter respectively. The arguments for and against multi and single time estimates are explored, looking particularly at the mathematical and the practical difficulties relating to the application of the former. The way in which the approach to the analysis of both Direct Costs and Indirect Costs, particularly the latter, varies substantially not only from organisation to organisation but from contract to contract within the same organisation, is also considered.

The objective of this chapter is, therefore, to provide an understanding of the need for planning and control and clearly define the individual characteristics of time and cost prior to a detailed examination of the time cost relationship in Chapter 4.

### 3.2 The Concept of Planning and Control

The current economic problems have created a situation in the construction industry where profit margins are small and contracts are scarce. In addition, the industry generally, has become more technologically advanced. It is apparent that the need to plan, and plan effectively, is becoming more and more important. The ability to plan and evolve effective control procedures may mean the difference between survival and liquidation/bankruptcy. The point made in Chapter 1 relating to the fact that many contracting organisation, even the large ones, have been forced into liquidation due to the financial difficulties encountered on a single contract is worthy of reiteration at this stage. These difficulties could often have been anticipated had an adequate control and feedback system been in operation, providing early warnings to management.

It is useful, at this stage, to define planning. Ross<sup>16</sup> describes it as "deciding in advance what has to be done, who has to do it, when it has to be done and how it has to be done". There has been a tremendous upsurge in the use of formal planning methods attributed by Steiner<sup>28</sup> to a number of factors that are relevant to the current situation in the construction industry. These are:

- i. The rapid rate of technological change.
- ii. The increased complexity of management owing to the growth and size and diversity of businesses.
- iii. Growing competition, and the need to forecast for longer periods of time when making decisions.

Strategic planning is described by Steiner<sup>28</sup> as "the process of determining the major objectives of an organisation and the policies and strategies that will govern the acquisition, use and disposition of resources to achieve these objectives". The concern in this research is, however, with tactical planning which refers to the process whereby "detailed plans are developed for the deployment of company resources to achieve strategic plans".

The major aspects of tactical planning are considered to be:

- i. The determination of alternative courses of action. This involves a search for alternative ways to achieve the objectives of the plan. This process must always involve the quantification and documentation of alternatives for the purpose of analysis.
- ii. The evaluation of alternative courses of action. This is concerned with weighing the desirability of alternative courses of action and in certain cases, may be reduced to mathematical selection when all variables can be quantified. This latter situation is unusual in the construction industry where most planning problems include a high percentage of intangibles and uncertainties.
- iii. The choice of alternatives. This is the point at which a decision is made and a course of action selected. This takes into account factors of expediency, time and cost.

Koontz and O'Donnel<sup>29</sup> consider that planning objectives should "indicate the end points of what is to be done, where the primary emphasis is to be placed and what is to be accomplished by the network of policies, procedures, rules, budgets, programs and strategies".

Ross<sup>16</sup> shows quite clearly that "planning is inextricably interconnected with controlling". However, if the construction industry operated in a totally deterministic environment and could, therefore, depend upon the flawless execution of plans by a perfectly balanced work force and organisation, there would be no need for control, results invariably being as expected. In practice, plans rarely remain on course and control is necessary to obtain the desired result. It is obvious that it is, in fact,

the results that are achieved that are the measure of progress not the plan itself and therefore it follows that personnel responsible for results should also be involved in the planning procedure.

Control is concerned effectively with three basic steps:

- i. Setting standards of performance.
- ii. Measuring performance against these standards.
- iii. Correcting deviations from standards and plans.

This involves, therefore, the measurement of performance against plan for individual and group activities. This criteria can usually be stated in terms of cost, time, quantity or quality. Time and cost, of course, constitute the basis of this research and are dealt with in detail in Parts 3.3 and 3.4 of this chapter. Quantity is generally easy to measure and quality is a common feature in judging the acceptability of a project in terms of its specification. The performance of the plan can be measured by site personnel. However, measuring performance purely by personal observation is time consuming and lacks precision. This situation is slowly changing due to the accelerated developments in the computer field, particularly the development of the micro computer and the potential it offers for site control using networks or similar models for measuring performance. Continuous comparison of the plan with actual performance enables the manager to instigate the control necessary for early correction of deviations. The uncertain nature of the construction process makes it impossible to treat planning and controlling as separate functions and the premise that "planning is inextricably interconnected with controlling", is therefore accepted in the context of this research.

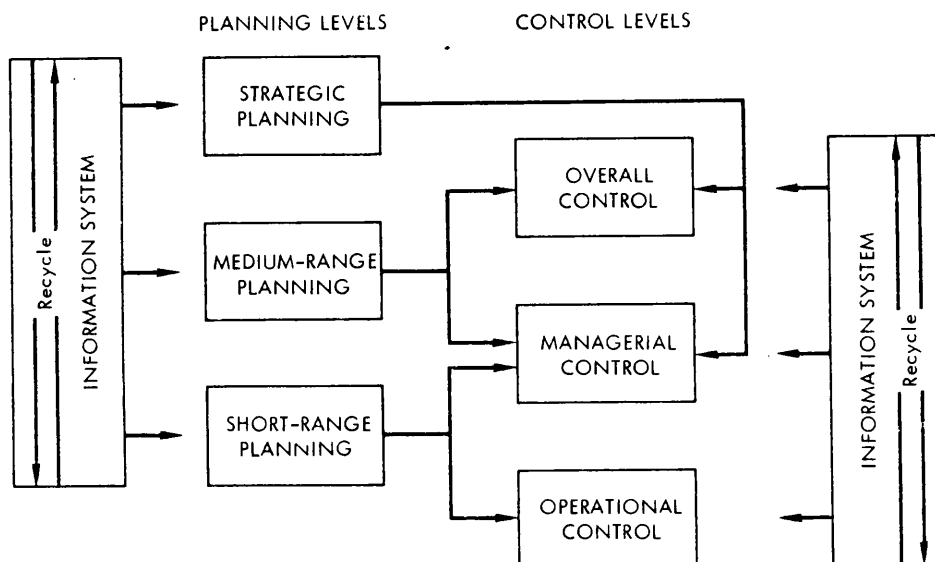


Figure 3.1(Ross<sup>16</sup>)



Figure 3.1 illustrates the integrative nature of planning and control.<sup>16</sup> Here Ross shows that planning and control processes are not static but dynamic in nature, hence their actual operation in practice is iterative as shown in the recycling process. He points out that "an additional integrative characteristic of these two activities is the frequent practice of designing control standards during the planning process. In practice it has generally been found that plans are operated more effectively where those persons responsible for control are involved in the planning process".

Ross also links the function of organising with planning and controlling (Figure 3.2).

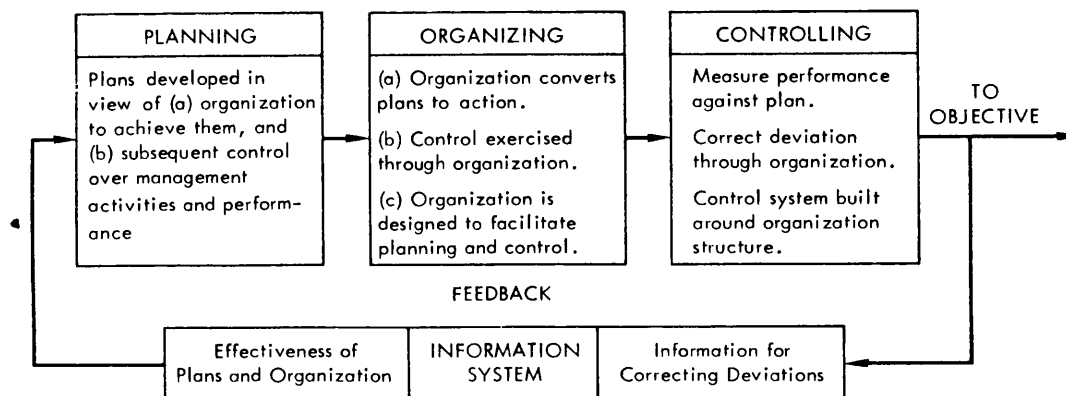


Figure 3.2 (Ross<sup>16</sup>)

In this diagram he shows that these three basic functions form a process that is "integrated, iterative and dynamic". It can be seen that the organisation is the vehicle through which plans go into action. The ability of the organisation to activate plans and maintain subsequent control must be taken into account in the planning and control processes. Having shown the relationship that exists between planning, controlling and organisation, it is not the purpose of this research to further investigate aspects of the organising function.

There are, of course, a number of obstacles to effective planning. These relate to the time span covered, unforeseen or unpredictable events, lack of information, the human factor and the costs of planning. As the time span of a plan increases the accuracy of the planning will tend to decrease accordingly, (see Chapter 2). This is due, in the main, to the fact that as the time span increases the probability of an unexpected event disturbing the plans increases and it becomes more difficult to forecast and anticipate

every likely possibility. It is therefore often assumed in the case of short term planning that forecasting is easier and the level of confidence increases accordingly. However even in the short term, situations change rapidly on construction projects. The implications of these changes which may be far reaching, can not be assessed intuitively and a complementary objective method of analysis is often essential for the evaluation of alternative courses of action.

Planning can be substantially affected by lack of sufficient information or by deficiencies in its accuracy and quality, often closely related to the time span involved. A balance must be struck between relying totally on imperfect information or postponing a decision until perfect information is available. The ultimate decision is very much a matter of executive judgement. It must always be remembered that effective control is to a large extent, dependent on the quality of site supervision and planning, however objective, in no way minimises the supervisor's role but should, in fact, complement and strengthen it.

The actual cost of planning must be balanced against the likely benefits obtained at the completion of a contract. The cost includes not only the salaries of the planners but also the cost of controlling and maintaining the plan in operation. In judging the costs it should be remembered that planning is not a luxury but a prime necessity for any organisation that wishes to operate effectively. The cost of planning must be balanced against such things as false starts, and the inadequate allocation and utilisation of expensive plant, equipment and labour that will inevitably result when planning has not been undertaken. It must be remembered, however, that planning is a means to an end and not an end in itself. More effective ways of implementing and controlling the plan must be continually sought and the cost of planning judged against the losses that may be incurred if it is not undertaken.

Planning is an analytical process and therefore certain broad steps can be identified viz. define the problem to be solved, get as many relevant facts as possible, organise the information available, analyse the information, select alternative courses of action, weight the alternative courses of action and decide which one seems best suited to meet the problem and put the decision on record. Urwick<sup>30</sup> states that "an effective plan should be based on a clearly defined objective, establish standards, use available resources to the utmost and be simple, flexible, and balanced". Planning is, therefore, an executive function which helps provide purpose and direction for those concerned with the management of an organisation.

This research programme is concerned, in the main, with pre tender, pre contract and short term planning in terms of time and cost. Weinberg<sup>27</sup> stresses the fact that "maximum control of time and cost" requires effective "construction management systems". He asserts that this form of control will be followed by "cost optimisation" and "best accomplishment of time control and project acceleration".

These specific aspects are, however, governed by, and must be operated within the parameters established by the organisation's strategic and policy plans. The need to plan at the pre-tender stage is immediately obvious when it is recognised that the likelihood of being awarded a tender in a competitive situation may well be dependent on the accuracy of such planning. It was suggested albeit in a half joking, half serious manner, during discussion with the sample companies that "many contracts were awarded on the basis of the estimators' mistakes." It is, however, equally apparent that an inaccurate plan and therefore an inaccurate estimate may not only result in losing the contract but conversely, due to error, obtaining a contract and sustaining a consequential loss that might easily result in even a large organisation being forced into liquidation. Pre-tender planning is a systematic approach to the problem of anticipating and forecasting and is, therefore, an essential factor in anticipating costs that are not readily apparent from the Bills of Quantities and the drawings at the estimating stage. Many essential items of information that may be of major significance in determining the cost and duration of a contract are often not available or are not communicated to the contractor at this stage. Examples of the latter quoted by the sample companies in this respect included situations where:

- i. The client required a certain section of work to be completed first.
- ii. The contract required phasing to suit the production of working drawings by the architect.
- iii. A local authority could not divert public services until replacement services had been installed.
- iv. Sub-contractors refused to install their equipment until the building was properly sealed and, in one case, the rooms were required to be of a specified humidity level before the equipment could be installed.
- v. Materials in short supply had extended delivery dates.

Given adequate information on factors such as these, the overall resources and experience of the company can be combined to guide the estimator to an accurate assessment of the quantity, sequence and most effective methods available for the completion of the work involved. In this way it should be possible to reduce or sometimes even eliminate, the risk of grossly

inaccurate forecasts that will adversely influence the tender figure. It should be noted at this stage that it is becoming more and more usual for contracts to be awarded not purely on the basis of the lowest price but also on the ability to complete the work in the shortest time. Certainly, every attempt should be made, at this stage, to identify the client's requirements in terms of completion target and to ascertain whether time or price, or a combination of the two, is the main consideration in identifying the most acceptable tender.

In practice, the duration of a contract is often not directly related to its value. For instance, it is not unusual for a contract exceeding say, £500,000, to be completed more quickly than one of half this value, as the operations involved and their interrelationship are often more complex in nature on the smaller contracts. The relationship and complimentary nature of the pre-tender plan and the financial breakdown of total costs for the project should be clearly defined, ensuring that the tender is time cost related.

Gilbreth (Spriegel & Myers<sup>31</sup>), states that "the determination of the path which will result in the greatest economy of motion and the greatest increase of output is a subject for the closest investigation and the most scientific determination". This statement relates equally to the pre-tender stage of a contract and the stage when the contract has actually been awarded and pre contract planning is being undertaken. It is at this latter stage, that the effectiveness or otherwise of the pre-tender plan becomes obvious when attempting to further develop and expand the investigation to cover the activities and phases of the work in detail before the actual construction activities begin.

Operating within the overall framework provided by the pre-tender plan, planners and site supervisory staff will need more detailed information on such factors as, activities involved in the work and their sequence; the duration of each activity; the resources, i.e. labour, plant and equipment, necessary to complete the activities within the planned duration. Note should be taken here of, the variable resource levels required for minimum cost and crash duration and the type and quantity of material required for each activity and the latest dates for delivery; details of specialist work including the relation to preceding and succeeding activities and the duration required for completion; the latest date when information such as detailed drawings, specifications and samples will be required; the minimum and crash costs for each activity, and the type of control system to be used to enable remedial action to be rapidly instigated.

It must be remembered that, to a large extent, the Bill of Quantities is a legal contract document (Chapter 2), and will be used in practice by the client or his representative to control the costs of each activity that constitutes the project, in that it summarises the build up of the tender figure. Unfortunately, it does not provide reliable basis for ascertaining labour, plant and material requirements or the costs pertaining to the activities that make up the contract, i.e. the traditional method of pricing a Bill of Quantities showing a "bulk rate", is insufficient to provide the planner with an accurate basis on which to determine the duration and cost of individual activities. Nevertheless, in so far as it is possible, the information used by the planner should compliment and correlate with the Bill of Quantities and Bill references should be included wherever appropriate. The Bill of Quantities is however far too general to provide a satisfactory basis for planning purposes, e.g. a description relating to concrete in columns of a given cross sectional area would, for planning purposes, need to be broken down into activities such as: concrete to column starter at ground level; concrete to columns ground floor to underside first floor beam; concrete to column starter first floor level; concrete columns first floor, second floor, etc. In addition, the significance of activities such as mixing, placing and transporting concrete would need to be taken into account.

It is still a common assumption that the earlier site activities are commenced the sooner the contract will be completed. In almost all circumstances the reverse is much nearer the truth. Failure to plan carefully and accurately before work commences on site will invariably delay completion and result in additional costs. It is unfortunate that, in practice, the contractor has great difficulty in obtaining the necessary co-operation and understanding from the architect and the client - who are often impatient and anxious to see the work commence. In this respect, it is essential that the architect, in his professional capacity, is aware of the implications and guides his client accordingly. While the ultimate decision on a starting date will be influenced by the size and nature of the contract, nevertheless, this general premise is applicable whatever the size of the contract.

When the contract is actually in progress, detailed attention must be given to planning, in detail, activities that occur a short time ahead, i.e. short term planning. The purpose of preparing a short term plan is to keep the master plan alive and responsive in the light of changing or unforeseen circumstances. In this situation continuous feedback and updating must be seen as an essential facet of the planning process. This aspect of planning

has been neglected in the past due, in the main, to the lack of interactive computing facilities capable of rapid, accurate and realistic updating. Such a facility would enable an accurate forecast to be made of the modifications necessary in the immediate future in order to recover lost time. The object being to return to the original programme wherever possible. Alternatively it may be that a project is running ahead of time. Although on the face of it this may seem an ideal situation, it may not be always advantageous to attempt to benefit by such a saving, in that it may seriously affect the relationship and cost of activities occurring later in the contract. Each activity to be carried out during the short period ahead should therefore be considered again in terms of the quickest method, the most economical method and the interrelated sequence of the work. The optimisation or near optimisation of time and cost should always be seen as a major factor in arriving at a decision as the quickest and the most economical methods are not always one and the same thing.

In order that the process of forecasting and planning ahead can be pursued to its ultimate conclusion, forecasting and planning must be undertaken on a regular basis by site management, in that they are responsible for producing the required levels of performance in terms of time, cost, quantity and quality. At this stage, control procedures must be undertaken in great detail to ensure that progress is following closely the pre-determined plan of events, and it is essential that problems and difficulties are anticipated before they happen thus reducing unnecessary delays to an absolute minimum. The planning and control of time and cost is further considered in Sections 3.3 and 3.4.

### 3.3 Time - Activity and Project Duration

The major parameters of activity or project planning are time and cost. This section concerns itself with the time parameter, i.e. the optimal time for performing the individual activities that constitute the project and the overall time for the project as a whole. The optimal timing for the project is a function of the technological order of the various project activities, the resources required and their availability and the cost of resources. The optimal time parameter may be deterministic or stochastic in nature. (See Chapter 5).

The input to the production model, whatever the industry, will include the major resources of labour, plant, materials and capital. Since the construction industry is subject to the vagaries of climatic

conditions the environment could also be seen as a major input. (Fig.3.3). To convert the model shown in Figure 3.3 to a productivity model, the parameter of time has been added. The input to the system is now time related and can be expressed in units of input per time unit. Similarly, the units of output can be expressed in output per time interval. Units of input may be expressed as man hours per activity, plant hours per activity, delivery periods for components and materials, the capital cost of time, etc. Similarly, outputs can be expressed as square metres of formwork fixed per day, concrete poured per day, etc.

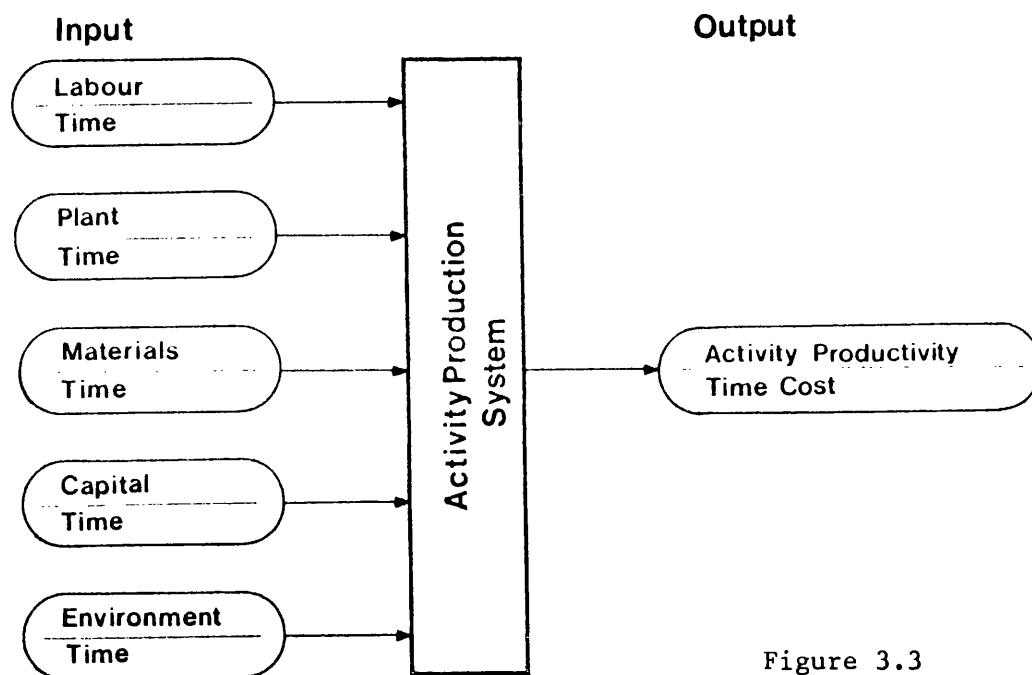


Figure 3.3

The production system is, therefore, directly related to time and the process of converting input to output is extremely complex. In order to ensure adequate control detailed planning is essential. The preparation of the plan and its implementation requires a detailed analysis of the inputs and the way in which they must be manipulated to produce the required output.

There are many time intervals that can be selected for the planning purpose, i.e. minutes, hours, days, weeks. For construction projects it is usual to express the time parameter in terms of days or weeks. It is, of course, necessary in certain cases to plan in greater detail, e.g. alternative methods of placing formwork ties when hours or even minutes might be more appropriate. Time intervals using days or weeks will normally relate to a standard eight hour day or a forty hour week. The time interval chosen must, of course, be followed consistently throughout the planning procedure.

In practice, the processes of time estimation follows the logical analysis of the likely sequence and interrelationship of project activities. The two are, however, closely related and the addition of time may require a reassessment of decisions on logic. Time estimates may be based on judgment, published labour constants or work measurement. The first approach, although widely adopted is purely subjective in nature. It was clear from discussion with the sample companies that although costs are calculated in some detail, the time for an individual activity or the project as a whole, is often simply a gross estimate based on experience with similar projects. This probably derives from the fact that in the majority of instances, the success of a tender relates directly to cost, whereas contracts do not, in the main, have time limitations in that the client is often not so directly concerned with the exact duration of the project. However, in the case of industrial projects time is often a critical factor and penalty clauses for failure to complete on time, are often included. In this case, the need to produce accurate time estimates is therefore as important as accurate cost estimates.

Published productivity constants are also used fairly extensively and are available from a wide range of sources, e.g. Spon,<sup>34</sup> Building Cost File<sup>32</sup> Laxtons,<sup>33</sup> etc. These figures refer, of course, to average productivity levels taken from different sources and geographical locations. This type of weighted average is not generally suitable for planning purposes in that it makes no allowance for the particular expertise and resources available to an individual contractor. Work measurement is used by a number of construction companies and includes the techniques of time study, synthesis from element times or synthetic data and analytical estimating.

The objective is to produce a stock of data relating to the principle elements of construction work providing a synthesis of the operations within the range of a particular activity. The simplicity with which synthetic data can be applied will depend very largely on the suitability of the classification system adopted. The advantages of the micro computer in this respect are discussed in Chapter 6.

Geary<sup>35</sup> states that "experience, assumption and common sense supported by historical records have in the past provided approximate estimates of the work content of building activities. These enlightened guesses, while useful, have certain limitations:-



- (i) They are general averages of past results, and do not take into account all the circumstances of the particular contracts from which they were obtained.
- (ii) No records can exist for jobs of a kind which the firm is doing for the first time.
- (iii) Fluctuations in the rate of working during a contract, caused by accessibility, different methods of working, etc. are usually not systematically analysed.
- (iv) The basis of much historical data are the operatives' time sheets and these are notoriously inaccurate".

He concludes that "work measurement enables the work content of jobs to be established in a form which overcomes these limitations", and suggests that a synthetics data library should be available for the use of planners and estimators.

Whatever the method adopted allowance must, of course, be made for such factors as overtime, quality, size, geographical location, height above ground, season of the year, etc., all of which may have a substantial effect on the accuracy of the planned duration. For instance, the time of the year may affect output by as much as 50 per cent.

Possibly the most significant single factor affecting activity duration is weather conditions. Certainly discussions during the research programme with planners and project managers sited weather factors as the most frequent cause of delay and uncertainty. It is considered however, that this factor is often sited when the underlying cause relates to lack of adequate planning and control. Moder and Phillips<sup>36</sup> suggest two basic approaches that may be used to allow for inclement weather, viz:

- (i) " by adding a weather activity at the end of the project as a whole,"  
or
- (ii) " by increasing the duration of each affected activity."

When an allowance is made as a single weather activity at the end of the project, the effect is to distribute the allowance to the individual activities in proportion to the time duration of each. This method is appropriate where a high proportion of the activities are likely to be affected by the weather, e.g. work in the ground. It will also be effective where a high proportion of the activities that establish the project's

overall duration have long durations and are themselves weather dependent. Where an allowance for weather conditions is made to individual activities, the allowance is often insufficient due to the common practice of starting activities later than the earliest starting date. The subsequent build-up of materials on site creates storage problems and results in capital being invested before it is necessary (section 3.5). It is considered that the most appropriate approach is to make allowance at the end of certain phases of the contract, i.e. after the groundworks have been completed. In addition, a further allowance can be assigned to those individual activities most likely to be affected by weather conditions.

The particular needs or motivation of the individuals making the final decisions on time estimates can have a significant effect on their accuracy. In practice a distinct "bias" is often apparent in this respect. It is suggested that time estimates often relate to what will be accepted as "reasonable" without causing embarrassment at some later date. The discipline involved in preparing a plan will have a significant influence in reducing "bias" in time estimates to a manageable level. Uncontrolled "bias" can have a serious effect on the determination of the critical activities that constitute a network and may well concentrate the attention of management in the wrong direction. This situation frequently occurs when planning sub contractors' work, where it is extremely difficult for the planner to obtain accurate estimates. In estimating the time parameter each activity should be considered in isolation and constraints such as delivery periods for components or materials should be shown as a separate activity, each with its own time estimate. For the purposes of this research a "normal level" of resource availability is assumed. This is the approach generally adopted in practice unless it is readily apparent that there are limitations on specific resources that make those particular activities resource dependent.

Time may be viewed as a constraint (cost is considered to be the other major constraint, Section 3.4), on the completion of an individual activity or the contract as a whole. Each activity takes time to perform and thus will have some duration associated with it. When project network analysis is used the time at which an activity commences is the maximum of the durations of the inwardly directed paths to that event, since all of the activities directed into the activity must have been completed. The project duration is then the maximum of the elapsed time along all the paths from the origin to the terminal node marking the completion of the project. The path with the longest duration is called the critical path and any delay in a critical activity will obviously cause corresponding delay in the entire project.

There are several objectives involved in the process of computing the basic time schedules, i.e. to determine the overall time or duration for the project as a whole, to determine for each activity, an early (EST) and late (LST) start time, an early (EFT) and late (LFT) finish time, and the total float and free-float sequence. These objectives are achieved by undertaking a forward and then a backward pass through the network. The forward pass commencing from the first activity on the network calculates the earliest start/finish dates for each activity. This is achieved by considering each activity in sequential order and calculating the earliest time at which it can start. Then by adding the duration of the activity to this time, the earliest time at which it can be finished is obtained. The next activity in the chain can start as soon as the preceding one is finished, so the earliest start for an activity is the same as the earliest finish of the previous activity. This process is continued until the whole network has been worked through. The earliest finish of the last activity is the earliest time at which the project can be completed using the given sequence and durations. The backward path involves repeating the process in reverse, i.e. working from the last activity to calculate the latest finish and start times for each individual activity.

A "critical activity is one where  $EST = LST$  and  $EFT = LFT$  so that there is no "float" time available to meet contingencies.

Activities with float have built-in flexibility allowed in their timing.

Float may be used in various ways in a project:-

- i. To extend the duration of non-critical activity so as to reduce the demand for labour and other resources.
- ii. To delay the start of some activities in order to take advantage of better weather or convenient construction conditions or simply to allow an element of flexibility in the management process.
- iii. To sequence certain non-critical activities that require common resources for their completion, e.g. a piece of equipment may be moved from one activity to another in a convenient rather than a logical sequence.

The duration associated with an activity can be a single number (the deterministic case), or it can be a random variable with a probability distribution, (the stochastic case). Activities in a complex construction project are usually unique to that particular project and are seldom of routine or repetitive nature. The deterministic approach assumes that the person making the decision on activity duration will provide a unique time estimate. There can therefore be a heavy reliance on past experience and intuitive judgement. There is much to be said for this approach when the ultimate activity controller is involved in the initial decision in that it places an obligation on him to achieve his own target time. It can, however, be argued that the uncertain nature of the

construction process does not lend itself to a deterministic representation. In order to reflect this uncertainty, attempts have been made to use stochastic models, that is, models in which some measure of the possible variation in activity duration is possible. This may take the form of a distribution showing the various probabilities that an activity will be completed in various possible duration times. Alternatively, it may be just some number that represents the standard deviation range or some other concept of variation. This latter method would not, of course, make any assumption about distribution form. The PERT approach for instance, does make specific assumptions about the form of the activity distribution. Although the true distributions are unknown.

MacCrimmon and Ryavec<sup>37</sup> in their study of the PERT model, state that "to the extent of their knowledge no empirical study has been made to determine the form of the activity distributions". They add "there would be many problems connected with such a study, not the least of which would be the non-repetitive nature of the activities".

In an attempt to provide accurate information on the probability of the activity target time being achieved stochastic models have been suggested using as many as five duration times for each activity. (Campbell<sup>38</sup>).

The approach using three time estimates has probably been the one most extensively researched. The three estimates correspond to b, the longest activity time likely if the worst happens (pessimistic\*), a, the shortest activity time if everything goes according to plan (optimistic\*) and m, the expected or model time (most likely\*). The "model" time should not be confused with the estimated "mean" time used in the deterministic case.

The three time estimates are weighted as follows:

$$\frac{a + 4m + b}{6} = \text{mean time}$$

and the variance is taken to be  $\frac{(b - a)^2}{6}$

This situation can be depicted in the form of a distribution curve. (Fig. 3.4). This curve is assumed to have only one peak, the most likely time (m) for completion. There is relatively little chance that either the optimistic or pessimistic estimates will be realised. Therefore, small probabilities (about one in a hundred), are associated with (a) and (b). No assumption is made about the position of point (m) relative to (a) and (b). It may take any position between the two extremes, depending entirely on the estimator's judgement. (Fig. 3.5).

\* PERT definition

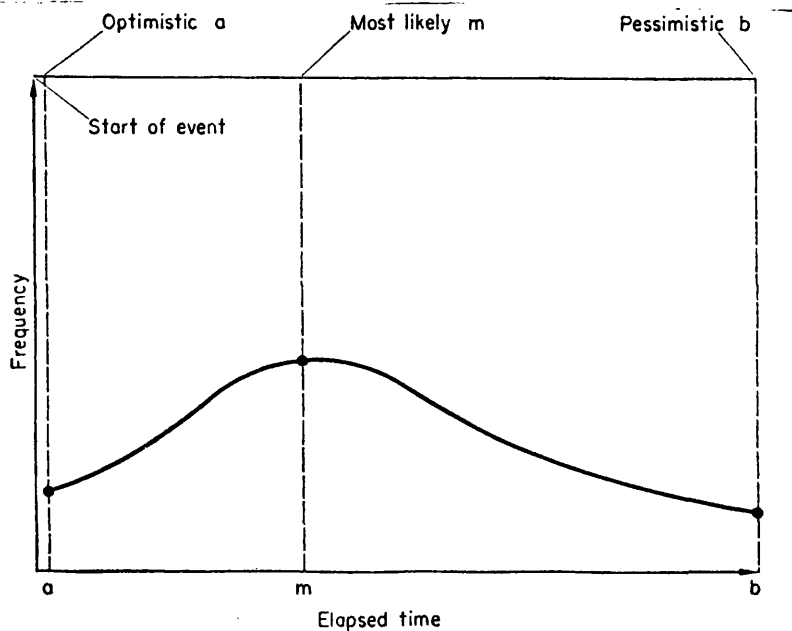


Fig.3.4

This is the approach used in the well known PERT model which assumes that the three estimates of activity duration are subject to a BETA distribution function.

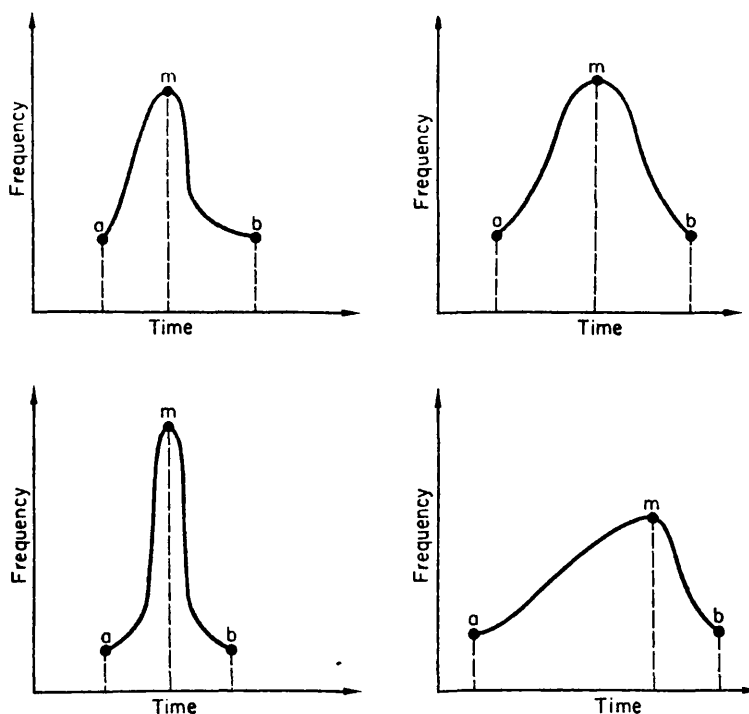


Fig. 3.5

Considering the three estimates it can be seen that, due to its weighting, the most probable duration for performing an activity will have a greater influence on the expected duration than the optimistic or pessimistic estimate. The expected duration of an activity may or may not equal the activity's most probable duration depending on the variability of the optimistic and pessimistic durations. If there is a wide range between an activity's estimated pessimistic and optimistic durations, the expected durations will be more subject to a higher degree of variability compared to an activity which had a small range in this respect. A wide range of estimates represents large uncertainty and, therefore, little confidence in the calculated expected durations.

The PERT model uses the BETA distribution (Fig. 3.4), to represent each activity's random duration, whereas in practice very few durations behave according to a BETA distribution. A more serious criticism in academic terms is that the formulas used in PERT are only approximations for the real values of the mean standard deviation and variance of the BETA distribution. Testing the values obtained using the PERT formula, MacCrimmon and Ryavec<sup>37</sup> found that many deviated substantially from the real values. For instance, they point out that "if the mode is near the end point of the distribution, the error could be as much as 33%. If the mode is more centralised then the error could be around 11%". Errors generally for the PERT calculated mean and standard deviation based on their studies, were within the band 10 - 30%.

A further difficulty associated with the probability theory used in the PERT model is that it uses the central limit theorem incorrectly. The central limit theorem states that the sum of like distributions such as the BETA distribution used in PERT will yield a normal distribution. However, in order to apply this theorem several conditions must be met, viz, each of the random variables represented by the probability distributions must be independent of one another and the distributions which are added to yield the normal distribution must all have the same mean standard deviations. These conditions are not met in the PERT model.

The PERT approach also ignores all non critical paths in the network in determining the project duration and its variance. The result is that the calculated project duration is often shorter than it would be if all paths were considered. This is referred to as the "merge event bias" problem. Klingel<sup>39</sup> has shown that in the case of ten parallel paths having reasonable levels of activity variants, the PERT calculated project duration may be in error by as much as 50%. It is considered that many of the difficulties referred to above, with respect to the use of the PERT model, stem from an unsuccessful attempt to build simplicity into a sophisticated probabilistic model.

More important perhaps than the above mathematical criticisms is the fact that when reality deviates substantially from the model, the user is then faced with the difficult task of remodelling his observations artificially in order to adapt them to the distribution function forced upon him by the model. This may well produce serious inaccuracies. In addition, the project manager may find it difficult to correlate the abstract model represented in the PERT BETA distribution, with the reality facing him at a particular stage of the contract. This factor was stressed several times in discussions with the sample companies. A further factor, and one on which considerable emphasis

was placed, referred to the fact that PERT required the planner to produce three time estimates for each activity, whereas in practice, it was "difficult" enough" to obtain one reliable time estimate. Certainly, the need to provide three time estimates was considered to be a significant factor in the singular failure of the industry to accept the PERT model.

An alternative approach using the Monte Carlo simulation method is suggested by Crandall<sup>40</sup> and Van Slyk<sup>41</sup>. In this approach random variables are selected from combined distributions applicable to the situation. Moder and Phillips<sup>36</sup> suggest that this approach "does offer the most economical solution to the merge event bias problem inherent in the PERT model", and it is argued by Crandall that "since the Monte Carlo Process generates a project completion distribution based on the simulation of many network schedules, the process should also yield typical schedules for control purposes". After careful study this approach was, however, considered impractical for control purposes on construction sites, due once again to the complex nature of the model. This applies particularly to the requirement to simulate project performance a large number of times and the problem of compiling the resulting distributions of project duration. Certainly such a task would be outside the range of the micro computer system described in Chapter 6. The requirement to provide several time estimates presents the same difficulties inherent in the PERT approach. In fact, the program described by Campbell<sup>38</sup> requires a selection of five time estimates for each point on the curve.

In summary, the findings of other researchers, particularly MacCrimmon, Ryavec and Klingel raise grave doubts as to the reliability and accuracy of stochastic models such as PERT when applied to the analysis of the time parameter. Certainly, there is no evidence to suggest that their use in practice is likely to provide a more reliable plan or control procedure. In fact the contrary has proved to be the case. Linking these findings with the clear preference for deterministic "one time estimates" on the part of the planners and site management it seems logical to conclude that the deterministic approach is certainly the most acceptable and most likely to be the most appropriate for the majority of construction projects. Accordingly, it is therefore the one used primarily in this research. The models suggested in Chapters 5 and 6 do not, however, preclude the use of multi-time estimates where these are considered appropriate.

### 3.4 The Characteristics of Construction Costs

As the term "cost" is used regularly in everyday speech it might be assumed that most people would have a reasonably precise understanding of its meaning. In fact, few concepts in economic theory are more elusive than the meaning of cost. The term cannot be defined with any precision in the absence of a careful preliminary exposition of the context in which it is to be used. In a general sense it is not possible, for example, to measure the cost of building an office block without stating whether the cost is a private or a social cost, the time horizon to be selected, what alternative uses are available for the resources employed in producing the building, the value of these alternative uses etc. The issue is further confused by the fact that the majority of the financial and cost accounting systems currently in use fail to differentiate between the different meanings of cost.

The importance of establishing a clear understanding of cost in the context of this research is readily apparent since one of the primary duties of management is to select and implement that plan which achieves a given objective at the lowest possible cost to the firm. Costs defined in this section, fall under the general heading of Private Costs, that is, costs which are relevant to a construction organisation. The concept of social cost and the way in which such costs can diverge from private costs are not considered.

One might define cost as the physical resources used in implementing a project e.g. the cost of preparing the foundations for an office block could include such items as 60 plant hours, 60 plant operator hours, 400 manual labour hours, 40 tons of steel and concrete. This statement in itself, however, is of little value in terms of measuring economic efficiency. 400 man hours is obviously less costly than say, 500 man hours but is 400 man hours plus 60 plant hours less costly than say, 1500 man hours? To answer this question it is necessary to measure both factors of production i.e. man hours and plant hours against a common measuring rod. This measuring rod which economists term a numeraire is obviously money.

Several of the classical economists (W S Jevons and A Marshall) put forward what they call a "real" theory of cost. This theory has a psychological basis. It suggests that cost consists of "the exertions of all the different kinds of labour that are directly or indirectly involved in making it (the product in question), together with the



abstinences or rather the waitings required for saving the capital used in making it. All these efforts and sacrifices together are called the real cost of production of the commodity". It can be seen in this context that the money cost is, in fact, the price paid for a product. This theory only applies to individuals, is highly subjective and cannot be applied to industrial organisations. However, it does confound the theory that cost necessarily implies the expenditure of physical resources.

With respect to managerial decision making, it is generally agreed that the relevant cost to be considered are incremental and opportunity costs. Looking first at the concept of incremental cost, a project uses a set of inputs, labour, plant, materials, etc. to achieve an output. Each of these inputs will normally have alternative uses. The incremental cost approach states that the cost of an input say, a given quantity of concrete is the value of the alternative use, to which this input can be put. This incremental cost could be measured by calculating the savings that will result if the project is not implemented. It could therefore be said to be a revenue definition of cost, i.e. cost is simply "the alternative benefit which must be sacrificed to achieve a given goal". Formally the situation can be stated as follows:-

Assume the inputs to a project P are  $i_1, i_2, i_3, \dots, i_n$ .

If we wish to calculate the incremental cost of input  $i_3$ , it is necessary to first identify the alternative uses of this input,  $a_1, a_2, a_3, \dots, a_n$ . Each of these alternatives must be evaluated and ranked in order of value, i.e.

Alternative uses of $i_3$ .	Value of alternative use.
$a_1$	$\pounds x$
$a_2$	$\pounds y$
$a_3$	$\pounds z$

where  $x > y > z$

The incremental cost of resource  $i_3$  for purpose  $a_1$  is  $\pounds y$  i.e. the value of the next alternative use  $a_2$ .

The concept of incremental cost is particularly important when a resource has no alternative use. This situation occurs quite frequently in the construction industry and it could be argued that the use of such a resource incurs no cost to the company concerned. This applies, for instance, to items of plant or transport that, at a particular point in time, are standing idle without an alternative use. At this point they represent no direct cost to

to the company, i.e. the indirect costs such as road tax, insurance, and possibly the wages of the driver concerned will exist anyway. Incremental costs are those expenditures which will be saved if the job is not undertaken, i.e. petrol, oil, maintenance, etc. It should be noted that incremental costs do not refer to price or tender, that the company presents to the customer, but are the costs associated with alternative uses of resources.

Opportunity cost measures the value of the alternative uses of the entire project, that is, the alternative outputs of the system concerned. It can be seen, therefore, that incremental cost measures the alternative uses of each input independently, whereas opportunity cost measures the alternative use of these inputs working as a system. Since the various inputs to a construction project can combine in various ways, the measurement of opportunity cost presents a formidable problem and is not considered further in relation to this research project. It can be seen therefore, that the incremental cost (and opportunity costs) approach is extremely important in decision making in that it forces the decision maker to compare alternatives, i.e. the costs of a project cannot be known until the alternative uses of the resources absorbed by the project are evaluated. When viewed in this way, it can be seen that cost represents one of the key concepts of management decision making. This view is substantiated by Peer<sup>42</sup>, who states that "there is no doubt that one of the principle factors in planning monitoring and steering the construction process is finance. Efficient control of project costs is the task which occupies most of the manager's time.

The traditional method of estimating building costs is to take off the quantities of each item and apply unit rates taken from the Bill of Quantities. Unit prices are not necessarily representative of the prices at which the work is actually carried out and contractors do not usually compete on unit prices but for jobs as a whole. It can be argued therefore that unit prices are relevant to the contractor only as a means of pricing work for interim payments and variations.

P A Stone<sup>43</sup> considering the problems of costing states that "it is generally accepted that the most accurate basis for costing is to base it on the programme of operations needed to carry out the job as a whole". Stone further states that "studies have shown that the coefficient variation for the unit costs of similar units of work range from about 10% to 50%. The range of prices would be about six times as great as this, thus the price given for a unit of a particular item of work might be a 100% larger or smaller than the average of the rates for that item of work. Clearly, little reliance can be put on the unit prices from individual bills". Stone

concludes that while the material content of a bill item is reasonably constant, the labour content depends on the way in which the operation is to be carried out and the way it relates to the other operations to be performed.

The general view expressed by the sample companies was that the contractor has the basic data needed to programme and cost the operations to be performed. The real value of this data could not be exploited however when the design was normally completed without consultation with the production team. It must be noted that in practice the design of a building often dictates the methodology to be used for performing certain activities and hence their costs. There are, however, problems relating to the availability and sources of basic data. Meyran<sup>2</sup> suggests that "we are in a vicious circle - lack of reliable data obstructs development of efficient management tools ... inefficient management restrains data gathering ... The intuitive mode of management which still characterises construction provides no time for collection or organisation and analysis of information".

Hackermeyer & Fine<sup>3</sup> state that "Much of the information in a firm's data bank if such a bank exists, rely on records maintained by foremen, or in certain cases, labourers, who present this information under limited cost headings." He adds that "gross inaccuracies existed and that many of the cost items were in fact, mis-allocated". They estimate "that for 200 cost headings about 50 items were often mis-allocated. For 2000 cost headings, as high a figure as 98% of the items were often mis-allocated". To surmount this difficulty many people have recommended the setting up of a universal data base with stored and organised information accessible to those concerned with the production process. Gurel-Armon<sup>4,5</sup> for instance, has developed a model for such an information system, the nucleus of which is a set of catalogues comprising standard descriptions of items in the construction process linked to data bases.

Green<sup>4,6</sup>, Armor<sup>4,5</sup> and Thurner<sup>4,7</sup> all identify a further problem by highlighting the "stochastic nature of construction costs", a feature that would make a universal approach extremely difficult, probably inappropriate or even impossible. It can be concluded therefore that costs not only vary from organisation to organisation but also from contract to contract within the same organisation. This conclusion was substantiated in discussions with the sample companies. However, the fact that "there are certain factors that remain constant whatever the situation" did also emerge. This latter aspect might warrant further investigation but is outside the scope of this research.

Costs relate to factors of production and are incurred by the contractor as distinct from prices which relate to sales. Costs are therefore incurred by the contractor and prices by the purchaser of the finished product. It is important to distinguish at this point, between the cost to the contractor, tender prices for building work and the final price of building works. Costs to the contractor depend on the prices of labour, materials, plant and management, together with the level of productivity achieved. In preparing a tender figure the costs and levels of productivity have to be estimated. The contractor, in fixing the tender price takes account of the expected costs and the market factors. These include both the state of competition and the nature of the contract. In the short term, when the contractors indirect costs are fixed, it is worthwhile taking on work as long as the prime costs are covered and there is some contribution to fixed overheads. Consequently, when work is short, tender prices may barely more than cover the prime costs, conversely, when work is plentiful, a substantial contribution to long term profits will be sought, therefore, tender price levels will fluctuate much more violently than cost levels. Contractors will also have fairly clearly defined expectations in relation to contract variations, Overall prices may be relatively keen but work expected to be omitted will be priced at relatively low unit rates, whereas work expected to be increased will be priced at relatively high unit rates.

Construction costs are characterised by several distinctive features which differentiate the construction industry from its counterparts in manufacturing and other industries.

In the main, construction projects are not conducive to mass production methods in that they are basically unique in terms of the environment under which the work is undertaken and the labour force employed. The work is performed by a wide range of skilled, semi-skilled and unskilled, labour, much of which is not in the direct employ of the main contractor. The control of costs is, therefore, project rather than process orientated.

Three major aspects of the construction costs can be identified, viz. estimating, data storage and costing, (figure 3.6) in the context of this research.

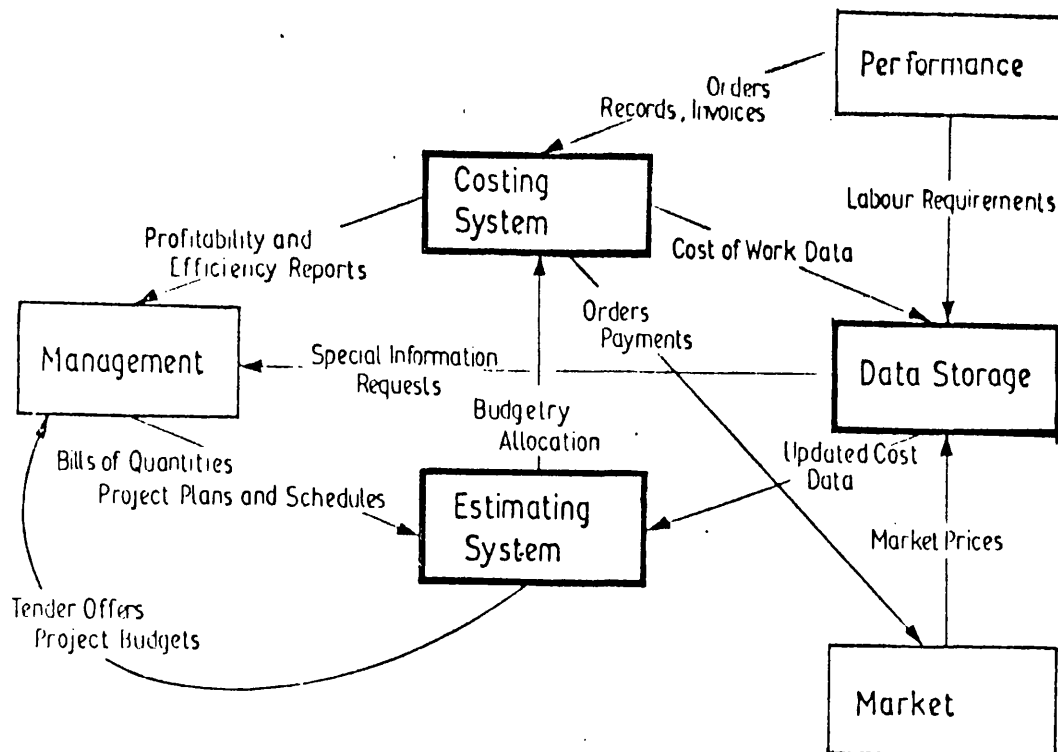


Figure 3.6

i. Estimating -

Here the cost of labour, plant and materials are determined, usually on the basis of a pre-measured Bill of Quantities for the project, (see Chapter 2). These estimates act as a basis for the tender bid and often act, although not suitable, as the budgetary framework for control once the work is in progress.

ii. Data Storage -

This refers to the method of storing and supplying labour and material cost information necessary for the preparation of the estimate, cost planning and control and as input data for optimising time and cost. (Chapter 4).

iii. Costing -

This refers to the recording, control and analysis of the various expenses incurred in the process of completing the project. In practice cost planning and control bear little relationship to 1 and 2 above and are often operated quite independently. This separation is caused initially by the "standard" structure of the Bill of Quantities, which is designed primarily to arrive at an estimate and not to control the project activities once the contract has actually commenced.

Although this research is concerned primarily with cost - it is nevertheless considered important to look more closely at the process of estimating in that the two are inextricably related.

i. Estimating

The estimating system is set up to enable a detailed "cost" build up to be prepared for the labour, material and plant necessary to produce the structure described in the Bill of Quantities and drawings. In practice therefore, the estimated project cost serves first as the basis for an agreed price between the owner and the contractor. The following factors are used in establishing the estimated cost:

- (a) Labour cost -  $C_L = h \times c$  where  $h$  = manhours required per unit  
 $c$  = the labour cost per hour

The labour cost is established by adding to the net cost per hour and additional charge or "oncost" for National Insurance etc.

- (b) Direct Material Cost -  $C_M$ . This includes a wastage coefficient for the material and the method used and the cost of transportation to the construction site.

- (c) Sub-Contractors Costs -  $C_S$

- (d) Cost of Temporary Works -  $C_T$

- (e) Equipment Cost -  $C_E$

$$C_E = h_e \times c_e \times u_e$$

Where  $h_e$  = equipment hours per unit  $c_e$  = the cost of equipment per hour

$c_e$  = the cost of equipment per hour

$u_e$  = the reciprocal of the utilisation coefficient

i.e.  $\frac{\text{total number of charged equipment hours on site}}{\text{Number of equipment working hours}}$

- (f) Indirect Site Expenses -  $C_I$  includes site preparations, supervision, energy, etc.

- (g) Overhead Expenses -  $C_0$  includes interest on capital, general management, and other general expenses at company level.

In addition, the unit prices and schedule rates that make up the estimate, form the basis of a comparison framework for payments and variations throughout the contract period. The system is used basically for the calculation of interim certificates and payments and as such is part of the contract documents. Interim payments are calculated by multiplying the measured work quantities by their respective unit prices. Although it is claimed that this method will indicate whether or not a project is "making a profit", this assumption is a dangerous one in that actual measurements usually run far behind the progress of the work and it is impossible to pinpoint losses on critical activities at any particular point in time. It is usual but not universal to separate direct costs from indirect costs, i.e. labour materials, equipment from costs such as supervision, temporary offices, etc., and profits and overheads. The main difficulty in practice is relating the description in the Bill of Quantities with the actual activity processes undertaken on the site itself, i.e. the Bill of Quantities will describe, for instance, concrete in foundations measured in  $m^3$  whereas in practice this will require further sub-dividing to take account of activities such as mixing, transporting and placing. The approach suggested in this research requires that costs be activity orientated thus reflecting the manager's needs for effective site control. It follows therefore, that activity based estimates, possibly based on Elemental Bills of Quantities, for example would form a suitable basis for such an approach.

## ii. Data Storage

Most of the data dealt with in the construction process falls into a hierarchical structure, i.e. it can be subdivided into projects, job areas within projects and within each major area, into job type or responsibility. These three major sub-divisions can be further sub-divided into functional groups and finally into a third dimension in relation to their status and permanency.

The objectives of data storage are twofold. First, to provide a data base, i.e. a collection of data related in some meaningful way and accessible in different logical orders. Secondly, to enable the user to reference the data in a logical fashion most appropriate to the problem under consideration. It can be seen from Section 3.3 that data relating to the time element can be

dealt with in the same fashion. The interrelationship identified in Chapter 4 shows that a data base with a common root for both time and cost would be extremely beneficial.

It is suggested that for the purposes of this research, a system of the type illustrated in Fig. 3.7 would be appropriate. This system is activity centred. It allows for the fact that an activity may use information on cost (and time) generated by other than its immediate predecessors. Conversely, information generated by an activity may be needed by several activities other than its immediate successors.

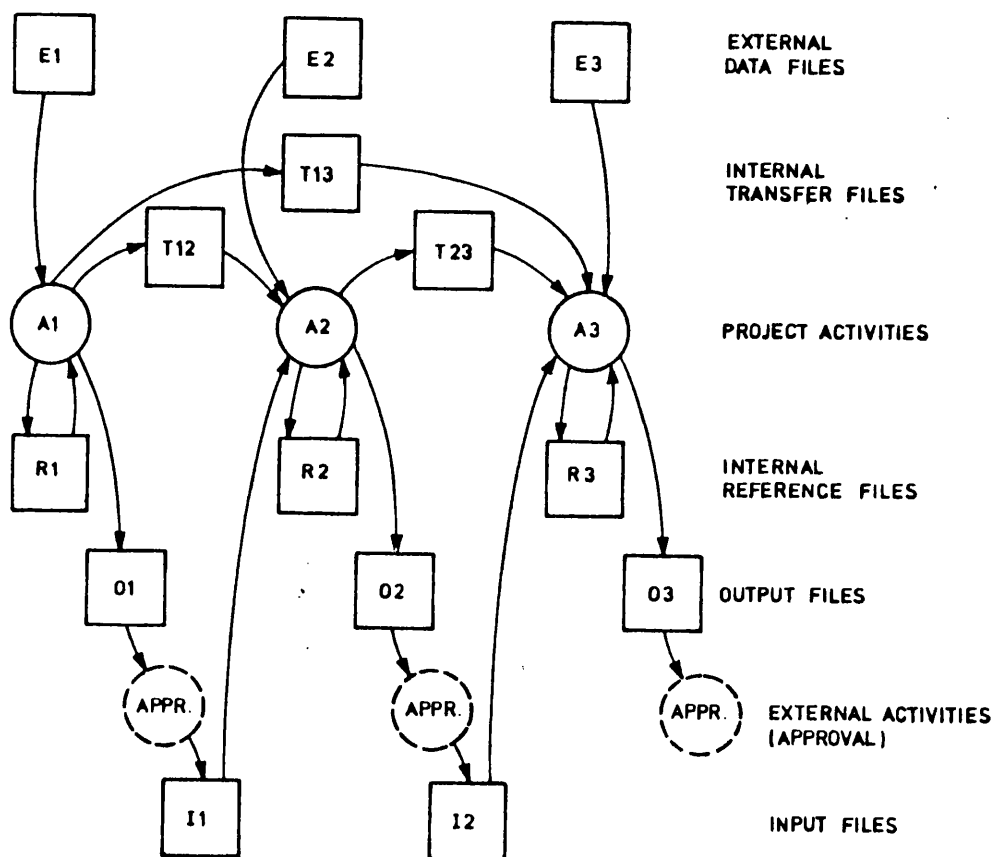


Fig. 3.7

In Figure 3.7 the information is organised into

- external data source E1, E2, E3,
- internal transfer files T12, T13, T23 between the internal activities,
- internal reference files R1, R2, R3 for use by the internal activities,
- output files O1, O2, O3 to the external activities,
- input files I1, I2, from the external activities.



It is essential that information required for costing, either for estimating or planning purposes is accurate and preferably based on work measurement (see section 3.3), reflecting the expertise of the company. It should be easily retrievable and should include such factors as:

- (a) Hourly rates of labour and equipment for specific activities.
- (b) Labour and equipment requirements (in days or hours per unit of work to be performed) based on site records and work measurement.
- (c) Market prices of materials, sub-contractors etc.
- (d) Feedback data for the contract under consideration.

### iii. Costing

It is essential that actual production costs can be ascertained quickly and accurately during the progress of the contract itself and that planned and actual costs can be easily compared. One way of satisfying this requirement is to establish cost centres (Fig.3.8) the most significant of which are identified below. These may require subdivision, to satisfy the needs of individual contracts.

- (a) Materials Cost Centre - responsible for the purchase of materials and supplying them to the construction site.
- (b) Labour Cost Centre - responsible for charging the project with labour wages, staff salaries, and social benefits. Wages will normally be a direct charge whilst salaries of supervisory staff will usually be an indirect charge.
- (c) Plant Cost Centre - responsible for the allocation and charging of plant to contracts on a daily, hourly or weekly rate, including maintenance expenses and repairs. This centre will also be responsible for the hiring in of plant not available within the parent organisation. Plant may be allocated to sites from the company's own plant resources or from external plant hire companies. Decisions relating to the relative advantages of hiring as opposed to buying plant will be significant.

- (d) Temporary Works Cost Centre - responsible for the provision of scaffolding, formwork, trench timbering etc. These items may be charged in various ways, such as overall time required, number of uses, or in certain circumstances may actually be purchased for the contract, and then written off or re-bought by the company when the work is completed. Costs may therefore be a direct or indirect charge to the contract.
- (e) Indirect Cost Centre - responsible for the charging to individual project's general expenses for the parent company as a whole.
- (f) Project Cost Centres - here all expenses that are directly or indirectly attributable to the contract will be charged. It is essential, of course, that direct and indirect costs are clearly differentiated. It is in this area that a number of sub-divisions may be necessary due to the variations occurring from company to company.

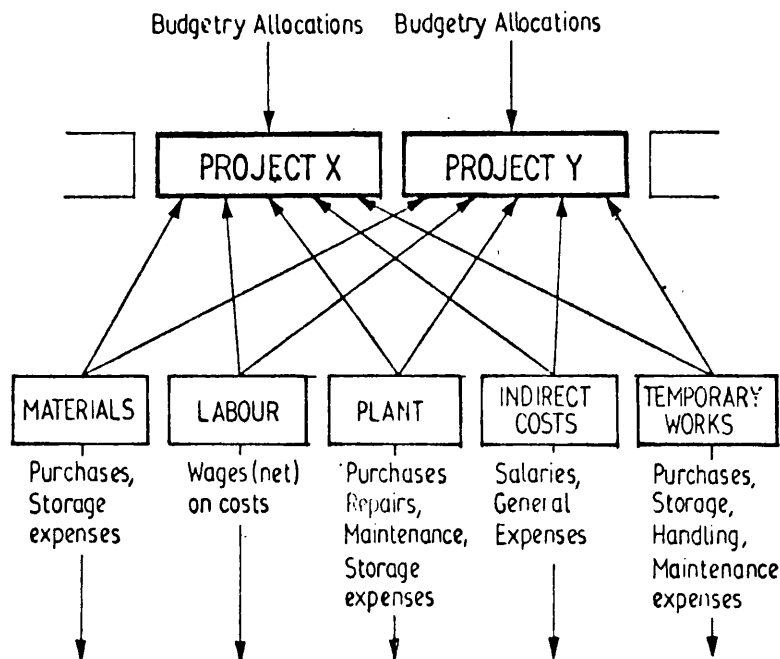


Figure 3.8

Costing procedures should reflect the accounting methods of the organisation as a whole. Whatever the system adopted it must ensure that the requirements of planning and estimating are inter-related thus ensuring that time and cost are not treated in isolation. It would be preferable, therefore, for planning and estimating departments, in the main, to be integrated, with combined teams planning and controlling both time and cost for specific contracts.

It is important therefore, that costs are prepared in such a way as to enable management to plan, co-ordinate and control all the resources essential to the satisfactory completion of the activities of any particular contract.

The differences between the actual results and the standards set will require analysis. These may be expressed in the form of variances which should identify where the responsibility for such differences really lie. The variances are normally of two basic types:

- i. Cost, price or rate variances which are accounted for by paying for the service at a rate or price different from the standard.
- ii. Quality Variance which is created by using more or less than the standard quantity of material, time or facility.

In order to improve profits management must be aware of all possible means of increasing revenue and decreasing costs. Examination of critical high cost areas can show fairly immediate benefits. It is essential that the relationship of one cost to another is taken into account in any such comparison. Variations in the cost of a critical activity may appear to result in an initial saving. It is likely however, that such a saving may, in fact, change the critical activities for the contract as a whole with the result that characteristics of uncritical activities are changed and they may, in turn, become critical. Such a variation may change the emphasis in terms of resource requirements and possibly necessitate a change of policy.

Effective cost control is difficult for construction contracts in that they often extend over considerable periods of time, therefore error, and drift are inevitable. Control is required to ensure that the need to provide flexibility can be met, overcome, and a stable situation created. Control is effective only if it can quickly identify variations in planned activities and feed back the information necessary to enable the controller to take remedial action. Each project

should have adequate resources to allow corrective action to be taken by, for instance, re-allocating the total project resources.

A cost control system should:

- i. Establish the cost plan in terms of physical work, value and time.
- ii. Report cost information at regular intervals.
- iii. Measure the physical progress against money expended.
- iv. Supply cost information to assist in solving problems and identifying alternative courses of action.
- v. Feedback deviations from the plan so that corrective action in terms of re-planning and re-allocation or adjustment of resource levels can be undertaken.
- vi. Provide a "cost" history of the project in order that management may learn from experience.

Successful control over cost depends upon the qualities of the estimate (or yardstick) which, in turn, depends on the amount of information which can be established at the stage in the life of the project when the estimate is being prepared. At the design stage control is often hampered by lack of definitive information whereas once the project has been awarded and is underway the project manager is often embarrassed and sometimes confused by the variety of information potentially available. The project manager is then faced with the problem of identifying the significant key or critical factors that will allow effective control of the project as a whole. Certain aspects of estimation are concerned with quantities which do not depend on time. On the other hand the majority of activities in a construction project fall more logically under the heading of forecasting and these forecasts are generally time dependent or dynamic activities.

It must be recognised, therefore, that unless estimates are properly prepared and relate to time factors the monitoring of costs and their comparison with estimates is often invalid. It should be pointed out that cost control methods will also vary with the type of contract under consideration i.e. there will be considerable differences in the method adopted for "fixed price" or "cost plus" contracts, for example.

It is essential to the manager that the level of monitoring detail which should be reported is adjudged to be that which allows action to take place where and when the actual situation and the cost plan diverge.

On the other hand the Project Manager is going to require information rapidly and in a form that is easily digestible. The monitoring system can be simplified and made more effective in two ways:

- i. By delegation of authority and arranging a filtering system so that only significant items are reported to the Controller.
- ii. By reporting critical or key ratios only using the exception criteria.

Efficient cost control could therefore be said to depend on:

- i. the preparation of a realistic estimate expressed in terms appropriate to control once the contract is actually under way;
- ii. monitoring commitments entered into against original estimate;
- iii. detailed cost control of individual activities with particular emphasis on critical activities allowing the exception principle to be operated and closely relating time and cost (Section 3.5) in such a way as to optimise performance;
- iv. quick and effective feedback showing deviations from plan and highlighting critical activities;
- v. the rapid comparison of alternative courses of action allowing informed decisions to be taken quickly, based on objective information.

This research is limited to the consideration of two major cost categories i.e. Direct Costs and Indirect Costs. The volume of published material defining these cost categories is enormous and it is not the intention to repeat it here or to further sub-divide the categories, e.g. fixed, variable, etc. It is, however, considered important to define briefly the terms as used.

Direct Costs - those immediately and wholly, associated with a specific activity.

The main components of direct cost are labour, plant and materials. There is a nationally agreed hourly rate which forms the basis of labour cost. However, the cost of employing one workman for one hour is very much greater than this and includes elements for oncosts, holidays, insurance and administration. The true cost of one hour of production work is the total wage bill divided by the productive hours of work during the period.

Plant costs are incurred in much the same manner as labour costs.

The true plant hourly operating cost is the total period cost divided by the number of operating hours during the period.

Whereas plant and labour cost accrue as time passes, material costs accrue as work is done. However, since materials are subjected to transport, handling and storage costs waste inevitably occurs. Consequently, true material cost comprises measured usage plus a waste increment.

Costs directly assignable to each network activity are added together to obtain the direct project cost. In the main, an individual activity cost will decrease as the activity duration increases. As the project duration is found by summing activity durations along the critical path, it therefore follows that the direct project cost will also tend to decrease with an increase in project duration. This increase will normally take place in a piece-wise linear fashion.

Indirect Costs - those, which though incurred in the main task, cannot be wholly attributed to one activity. There are two main sub-divisions:-

- i. Overhead Costs - necessarily incurred in providing a generally required service, e.g. accommodation.
- ii. Oncosts - unavoidably incurred due to ineffective time or work not directly productive.

Overhead costs fall into two main categories, General and Site.

General overhead costs are incurred in maintaining the permanent establishment of the company. Though related to the trend in turnover they tend to increase in steps and not to fluctuate with short term trends. They are not directly profitable and are, therefore, apportioned to the units of work.

Site overhead costs are concerned with maintaining necessary services during the construction period of the contract. Depending upon the nature of the contract they can be individually identified or apportioned.

Oncosts - The complexities of technical interrelationships in construction are such that the proportional requirement of different resources continually varies. It is, therefore, not possible to employ fully all the men and all the machines all the time, though they incur cost all the time. Consequently, costs, which cannot be directly recovered, are incurred. These oncosts can vary greatly but given equal management calibre and standard operating practice they should be consistent for work of a similar nature.

Direct costs are generally well understood in the construction industry and within the framework of the definition given above, precise values are not significant to the research. The same can be said to an extent for indirect costs. However, they are more complex and two approaches were considered:

- i. Simply to accept or slightly modify, as appropriate, existing indirect cost data, as in the case of direct costs.
- ii. instigate a special study.

If ii. were adopted, a possible approach would have been to study the organisation structure of a large firm with respect to overhead costs in general. It would, however, be necessary to produce an organisation chart identifying the roles of people in the organisation and apportion to them, percentages of time devoted to particular projects. This could be divided into two categories, (a) those concerned with production work i.e. estimators, production controllers, etc. and (b) those employed to provide a service to staff, i.e. typists, telephonists, etc. (service personnel). There is, of course, a third category - those who are based on site, who would be charged to their respective sites. The study would have entailed:

- i. determining the overall costs of running Head Office, District or Regional Office;
- ii. allocating the resources in Head Office to a particular project;
- iii. using the information given in (b) above and apportioning the costs in (a) above between the various sites.

The alternative was to investigate the position on a recently completed project. However, once again the identification of reasonably precise indirect costs was extremely complex and included a wide range of factors. The complex nature of overheads and the time involved in such a study ruled it out completely. Indirect costs were allocated in different ways by the sample companies i.e. added to unit rates or percentage lump sums on the net estimate and the approach varied from contract to contract and even from estimator to estimator within a particular contract. The value of indirect costs is therefore subject to the "whims" of each individual company. There was, therefore, no need or value to be gained from undertaking a special study of indirect costs. The assumption made is that indirect costs have two main characteristics; they increase with time and the rate of increase tends to vary linearly. Such costs can, however, be expected to have different rates of increase depending upon the particular contract organisation and site location and they are unlikely to have the same value for all contracts being performed by the same company. It should be noted that costs which are indirect at one level may become direct at a higher level. The classification of a cost may therefore vary depending on level.

The complexity and volume of data and information associated with construction projects has proved extremely difficult to handle in the past and has to an extent, acted as a disincentive, particularly to site management, in relation to a commitment to detailed planning. The relationship that exists between time and cost has clearly been neglected. This relationship is a complex one and any attempt to optimise it is only possible where a computing facility is available. Such a facility must be flexible, fast and reliable. The significance of the micro computer and its interactive nature in planning and control is discussed in Chapter 6.



## CHAPTER 4.     MODELLING THE TIME COST RELATIONSHIP

### 4.1     Introduction

Chapter 3 examined in some detail, the parameters of time and cost in that it is considered that these represent the two major constraints on the completion of a project. It is claimed that individually, both time and cost are given detailed attention in practice and the planning and control of both has been the subject of much research. This chapter commences by looking at the interrelationship that exists between these two parameters.

The remaining sections look at the problem of modelling the two parameters, concluding with an examination of existing models, highlighting their limitations. This chapter therefore sets the scene for the development in Chapter 5 of specific time cost models designed to determine the minimum project costs associated with each feasible duration of multiple activity projects.

### 4.2     The analysis and use of costs for cash flow requirements

Emerging from discussions with the sample companies was the clear impression that the time parameter is planned, sometimes in considerable detail and controlled using networks and/or bar charts. In addition all these organisations considered themselves to be cost conscious and confirmed that their major objective was to complete all projects at the least possible cost. They did not, however, give serious consideration to the relationship between these two parameters and, in fact, considered the cost of attempting to do so quite prohibitive. Accepting that for any activity or for any project there is a range of possible durations their difficulty was to determine which duration should be selected in order to arrive at the optimum cost for an individual activity or for the project as a whole, and there was no facility available to achieve this other than intuition and experience.

It was generally accepted that in order to decrease the duration of any particular project, "more money must be invested, i.e. the acceleration of a project invariably implies allocating additional resources to it with a resultant increase in costs".

It was not, however, generally appreciated that additional resources need only be allocated to critical activities, i.e. those that directly affect overall project duration. In practice the natural tendency, when a project falls behind schedule, is to apply an intense effort to all activities. The assumption being that this will effect a rapid improvement in the situation. However, it is only the critical activities which have an effect on the duration of the project and so it is these on which management should concentrate. Speeding up non critical activities may give the impression of rapid remedial action but will not, in fact, reduce the project duration, therefore additional costs can be incurred unnecessarily.

Accepting the premise that there is an identifiable relationship between time and cost in the main, although not always, (see iii below), direct costs will increase when an activity duration is decreased. There appear to be three major ways in which an activity duration can be decreased on construction projects, viz:

- i. By working overtime, i.e. increasing the number of hours worked per day or per week, but retaining the same resources on the activity.
- ii. By increasing or otherwise changing the resources used on the activity to achieve a greater output of work.
- iii. By using a different method of construction, e.g. pre-cast as opposed to in-situ wall or floor construction - in this case a reduction in duration may not necessarily imply an increase in cost.

In many cases, combinations of the above can be chosen for any one activity thus giving a substantial number of alternative ways of performing that activity. Each of these will give rise to a particular activity duration and an interrelated direct cost.

These factors are now illustrated by considering the simple project shown in the form of a network diagram in Fig. 4.1.

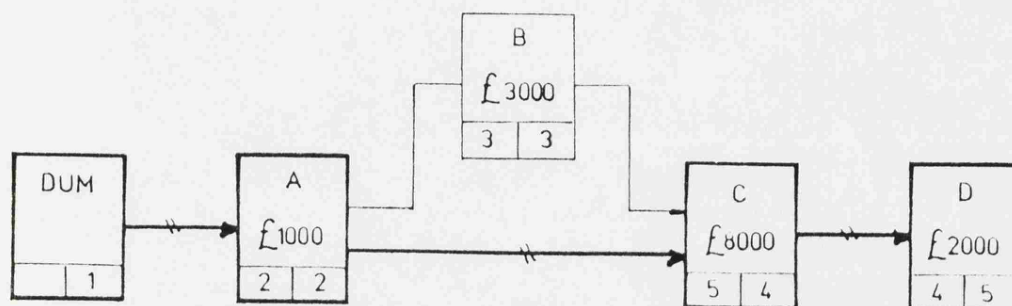


Figure 4.1

By converting the network to a bar chart (Fig. 4.2), the required expenditure on each activity for each time unit of the overall duration can be collated to give a weekly and cumulative total, giving the planned expenditure for the project.

	1	2	3	4	5	6	7	8	9	10	11
	500	500									
			1000	1000	1000						
			1600	1600	1600	1600	1600				
								500	500	500	500
Weekly Totals	500	500	2600	2600	2600	1600	1600	500	500	500	500
Cumulative Totals	500	1000	3600	6200	8800	10400	12000	12500	13000	13500	14000

Figure 4.2

Figure 4.3 expresses this information in graphical form providing a cash flow forecast for the project and allowing financial provision to be made accordingly.

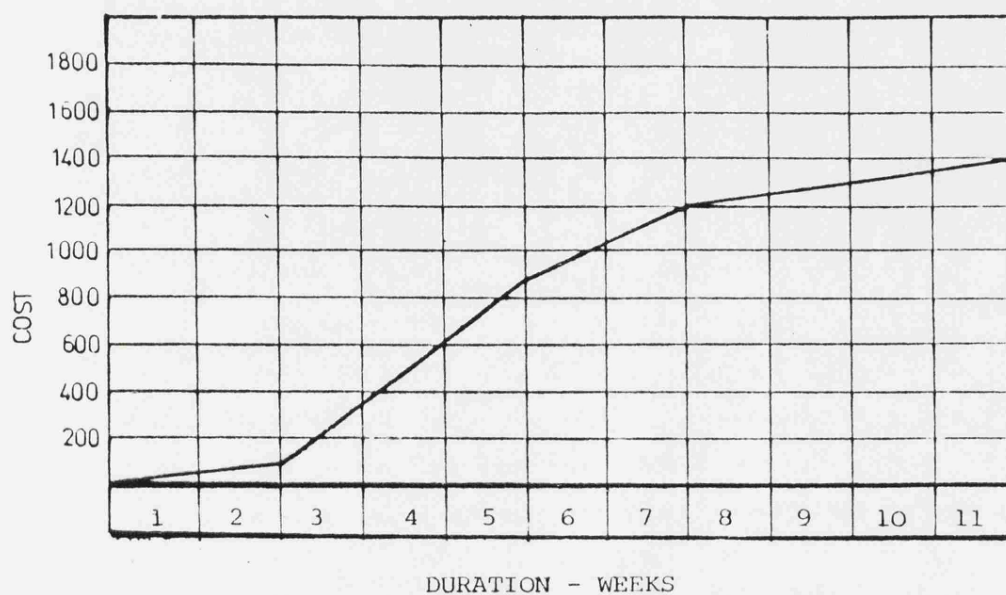


Figure 4.3

By identifying planned expenditure in this way progress can be checked by comparing actual cost and planned cost. To illustrate this point further assume that after five weeks duration the project shown in Figure 4.1 has progressed to the stage shown in Figure 4.4. It can be seen that the problems encountered during Activity 1 have added to its duration with the result that the duration of Activity 3 had to be reduced to meet the target date. Actual costs shown before the end of week 5 have also increased but it has been assumed that Activity 2 will still be completed within the planned cost of £3000 and Activity 3 still costs £8000 overall.

						Time Now					
	1	2	3	4	5	6	7	8	9	10	11
	1000	500	500								
				1200	1200	600					
				2000	2200	1900	1900				
								500	500	500	500
Weekly Totals	1000	500	500	3200	3400	2500	1900	500	500	500	500
Cumulative Totals	1000	1500	2000	5200	8600	11100	13000	13500	14000	14500	15000
	Actual Cost					New Forecast Cost					

Figure 4.4

Presented in the form shown in Figure 4.5 this information can be used for purposes of budgetary control.

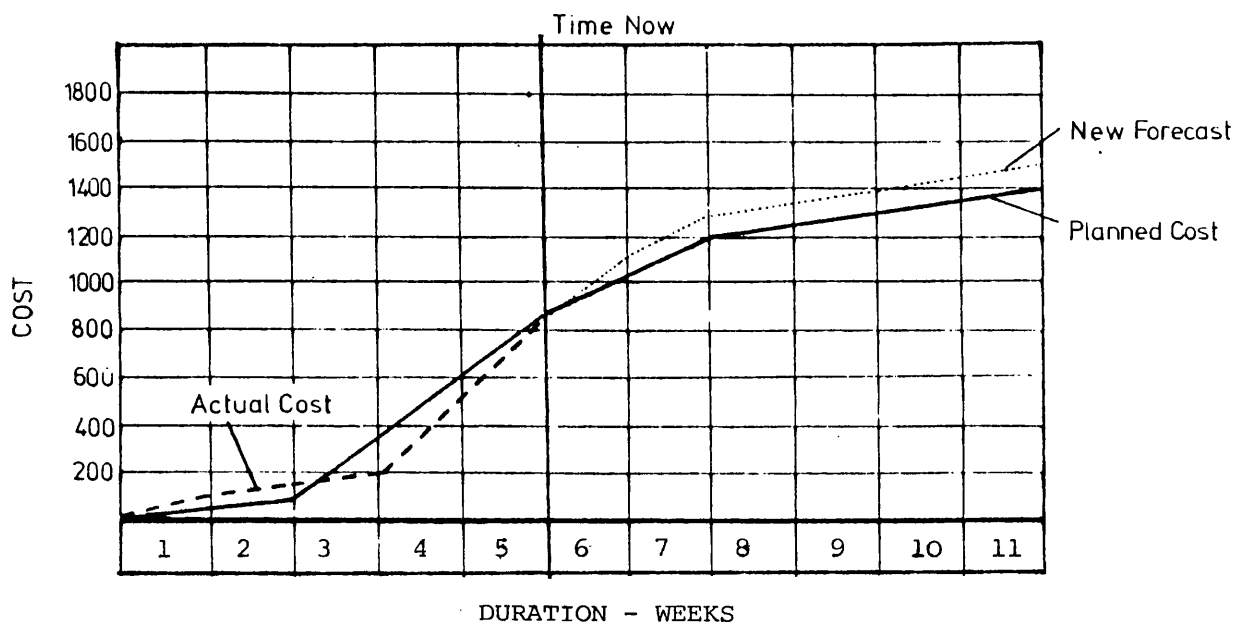


Figure 4.5

To develop this situation further, assume that each activity for the project shown in Figure 4.1 has the following budget allocations:

Activity 1	£1000
Activity 2	£3000
Activity 3	£9000
Activity 4	£2500

The resultant budget valuation for the situation illustrated in Figure 4.4 is set out in Figure 4.6 and the forecast profitability would be that shown in Figure 4.7.

	Time Now										
	1	2	3	4	5	6	7	8	9	10	11
	500	250	250								
				1250	1250	1000					
				2250	2250	2250	2250				
								750	750	500	500
Weekly Totals	500	250	250	3500	3500	3250	2250	750	750	500	500
Cumulative Totals	500	750	1000	4500	8000	11250	13500	14250	15000	15500	16000
	Actual Cost					New Forecast Cost					

Figure 4.6

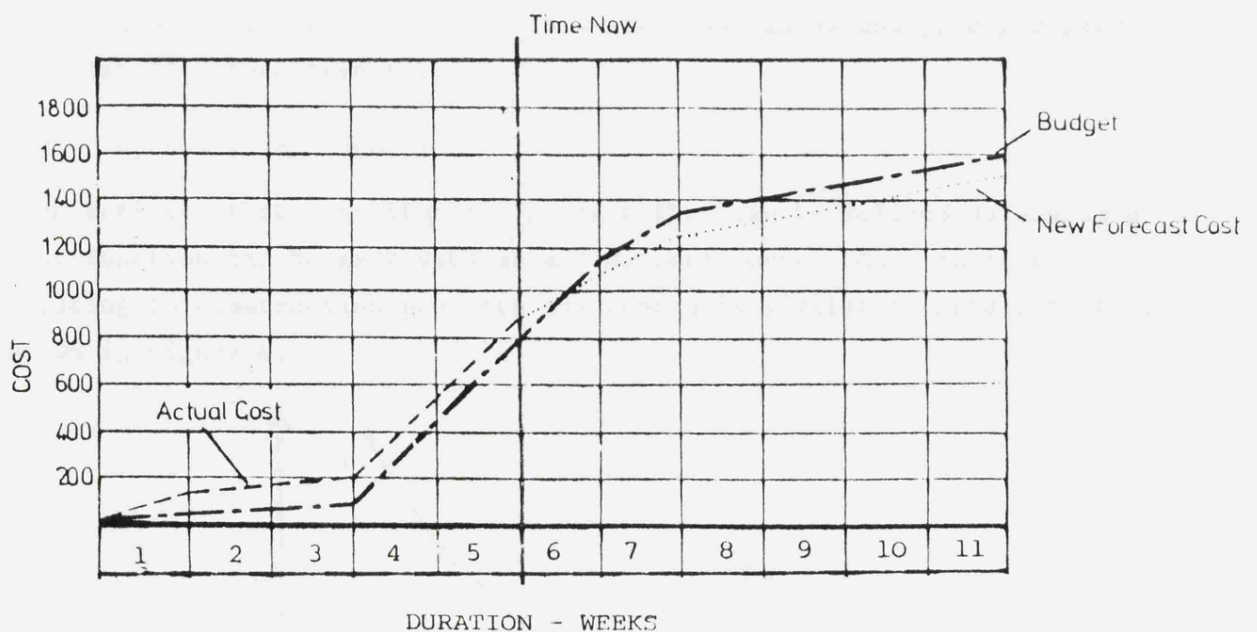


Figure 4.7

If the unavailability of finance is a limiting factor on the rate of progress that can be achieved for this particular project, then a resource analysis exercise can be carried out with cash as the resource using cumulative figures. Assume therefore, that the finance available is as follows:

At the commencement of the project	-	£3000
At the end of week 4	-	a further £9000
At the end of week 7	-	a further £2000

In this situation the limit and resource loadings would be as illustrated in Figure 4.8.

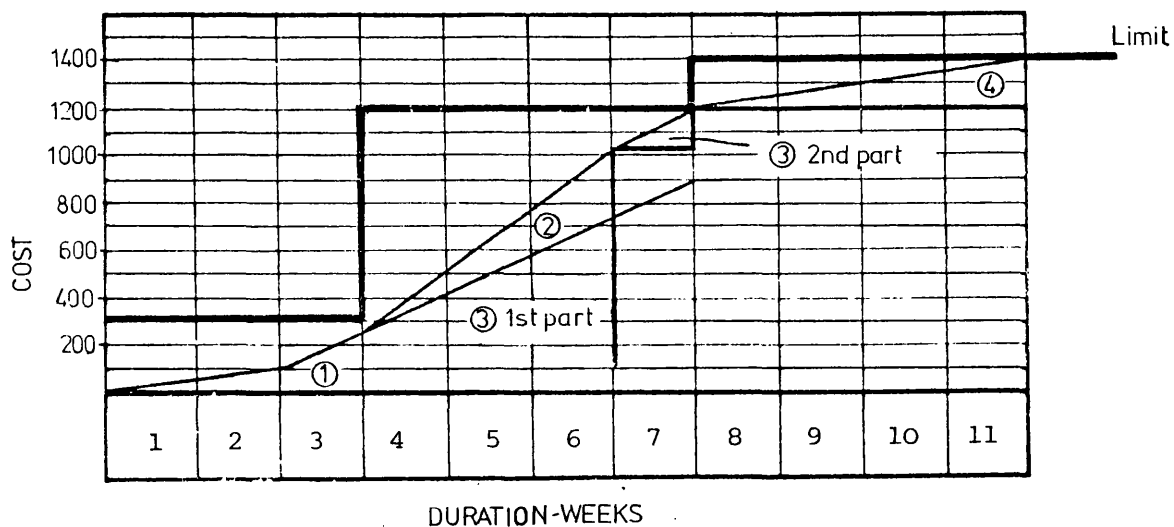


Figure 4.8

This example illustrates the way in which cash can be analysed and used for cash flow requirements.

#### 4.3 Activity Cost Functions

Each activity that constitutes a project that can be defined as having a cost function can be expressed as a time cost curve. Cost functions relating to construction projects are generally similar in nature to that shown in Figure 4.9.

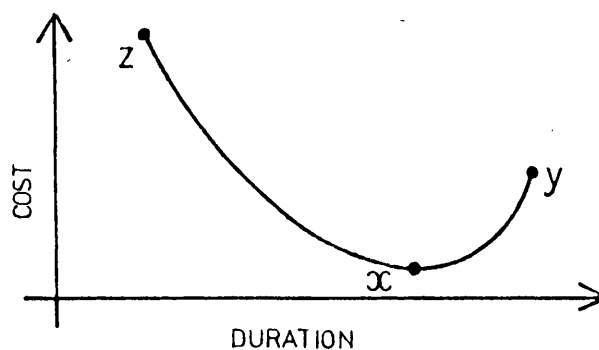


Figure 4.9

For each activity or for that matter, for a whole project, there is an optimum combination of men, equipment and method that will result in a minimum cost for that particular activity or contract. As more operatives, more equipment, or more expensive equipment is used, generally speaking the duration will be reduced and the cost will increase. Similarly, if insufficient manpower and/or plant are used, the overall duration will increase and there will be a related increase in cost. To illustrate this point, consider a simple activity where one man is used to excavate an isolated section of underpinning and the size of the excavation is such that only one man can work at any one time. Assume a duration for the activity of five days (40 man hours), and a cost of £80. If shifts are worked and two men used, it would be possible to complete the activity in half the time i.e. two and a half days. There would, however, be a shift differential to pay, increasing the cost to say, £90. If a third shift is introduced the time taken to complete the activity would be further reduced to one and two third days but due to the further shift differential involved the cost would increase to say, £100. If the first man is not given sufficient information concerning the exact nature of the task, it may, in fact, take him six days at a cost of say, £96. Plotting this information we have a typical cost curve for a construction activity (Figure 4.10).

In the main, this research project will be concentrating on the left hand portion of time cost curves evolved in this way. The right hand portion or "dragout" will, to a large extent, be automatically eliminated.

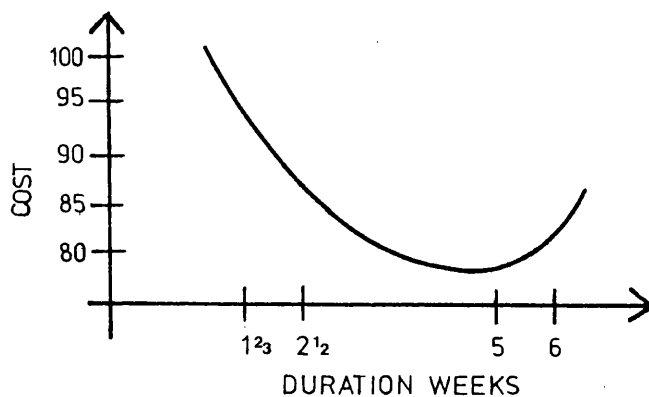


Figure 4.10

In this research the point on the curve which produces the lowest cost and the shortest duration associated with this cost will be referred to

as the normal or Minimum Cost Duration (Mcd). The cost of completing an activity in this time is referred to as the Minimum Cost (Mc) (ordinate x Figure 4.9). The ordinate x represents the time in which the activity may be completed at the minimum cost. In other words the minimum cost of the activity shown in Figure 4.11 is £1000 and if this sum is allocated to the activity it cannot be completed in a shorter period than 5 weeks,

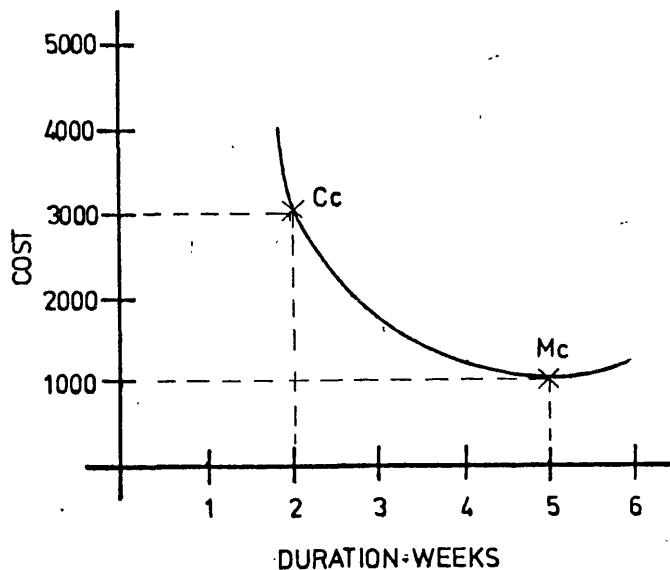


Figure 4.11

The Mcd is calculated by finding the most economic way in which the job may be completed. This assumes, however, that no matter how much longer the activity is allowed to take, it will cost no less, whereas the cost may in fact rise, (ordinate y Figure 4.9).

The Mcd does not, of course, represent the minimum duration in which the activity may be completed. Since, if the duration is reduced, this will result in an increase in the activity cost. Similarly, by increasing expenditure, the job may be speeded up, (ordinate Z Figure 4.9).

To define the Mcd as the lowest cost point may not be sufficient to pinpoint the required duration. This can be illustrated by considering a suspended floor slab for which the placing time is 240 man hours. It is possible in this situation to have four operatives working simultaneously with no decrease in efficiency or increase in cost. Therefore the duration may be 240 hours or 60 hours, at precisely the same cost. The Mcd therefore is 40 hours, i.e. the shortest time the activity can be completed giving the lowest cost. The activity still, of course, requires a total of 240 man hours. In the situation depicted in Figure 4.11 it has been calculated that the Mc is £1000 at a Mcd of 5 weeks, and it can be seen that if the duration is reduced to 4 weeks, the cost will be £1250. If the duration is further reduced to 3 weeks, the cost



will be £1600 and if it is again reduced to 2 weeks, the cost now rises to £3000.

At this stage the curve rises so steeply that there is little point in considering any further reduction in the duration as it would only result in a disproportionate increase in cost. The duration at which this situation occurs is referred to in this research as the Crash Duration (Cd) and the lowest cost associated with completing the activity in the crash time as the Crash Cost (Cc). The crash position on the curve represents the absolute minimum duration in which the activity may take place. Any additional manpower and/or plant will only result in an increase in cost and will not produce a corresponding decrease in time. The rate of increase in cost for a unit decrease in time is referred to as the Cost Slope, i.e. the slope of the straight line joining the minimum and crash ordinates, this can be expressed as:

$$\frac{\text{Crash Cost (Cc)} - \text{Minimum Cost (Mc)}}{\text{Minimum Cost Duration (Mcd)} - \text{Crash Duration (Cd)}}$$

Referring again to Figure 4.11 we see that the Mc is £1000 at Mcd 5 and that the Cc is £3000 at Cd 2. The maximum possible saving in time is therefore, 3 weeks (Mcd-Cd) at an increase in cost of £2000 (Cc - Mc). The slope of the Crash Cost Curve is therefore:

$$\frac{Cc - Mc}{Mcd - Cd} = \frac{2000}{3} = \text{£666/week}$$

Whilst it is the intention, in the main, in this research programme to represent time/cost information on precedence diagrams it must be pointed out that certain activities will not have a time cost curve, when the activity on the arrow approach is used. This applies, in particular, to dummy activities that are inserted in this type of network diagram for the purpose of logistics only and have, therefore, no duration and accordingly, no cost. Therefore, by definition Minimum Cost Duration, Minimum Cost, Crash Duration, Crash Cost and Slope of the Crash Cost Curve will all be zero. Another situation worthy of note relates to the delivery of materials, or components. Normally, the cost of material or component deliveries is considered as pertaining to the activity in which the material will be consumed. It follows therefore, that a delivery will always have a cost value of zero. It will, however, have a duration. Therefore, Minimum Cost Duration equals Crash Duration, Minimum Cost equals Crash Cost, equals zero, and the Slope equals zero by definition.

It may, however, be possible, under certain circumstances, to decrease the delivery time of a particular material or component by the payment of a premium. In this circumstance the following relationships apply.

Minimum Cost Duration	=	original delivery time
Minimum Cost	=	zero
Crash Duration	=	new delivery time
Crash Cost	=	additional premium
Slope	=	additional premium
	=	<hr/> original delivery time - new delivery time

Within the limits of the Crash Cost and Minimum Cost Durations there is, of course, considerable scope available for selecting the duration of individual activities in a project, each range of selections will lead to a different solution and in consequence a different overall project duration. Conversely, it is possible to vary the magnitude of individual activities and still obtain the same overall project duration. In this situation management is in a position to evaluate the merits of alternative solutions prior to making a final decision.

There are, of course, many criteria to be taken into account in a decision making situation such as this, many of them intangible in nature. The emphasis in this research focuses on cost and the optimisation or near optimisation of the relationship between time and cost.

When planning a project for minimum cost consideration must be given to the variables that arise and the factors that cause them to vary, viz:

- i. The cost of productive work will normally increase where it is necessary to complete the work more quickly, i.e. Crash Durations cost more than Minimum Cost Durations due to such factors as overtime working, inefficiencies associated with "over resourcing" and the use of unsuitable or badly matched plant.
- ii. Although indirect costs are not being considered in detail at this stage, it is important to appreciate that as the project duration increases standing overheads will also increase whether production is taking place or not. In this context indirect costs relate to such factors as site supervision, insurance, canteen facilities, etc. and in certain circumstances may also apply to static plants and equipment such as tower cranes, batching plants, hoists, and scaffolding.

- iii. In certain circumstances it may be advantageous to increase the cost of an activity in order to reduce the overall project duration. For instance, when a bonus and penalty clause of £100 per day is in operation it would be logical to spend up to £100 a day to eliminate the delay and attempt to bring the project back on target.

Accepting on face value, the premise postulated in i. above, it is apparent that when duration is reduced there will be a diminishing return for each extra pound spent. This can, however, be minimised by concentrating first on the critical activities, and identifying those that will incur the least additional cost when accelerated. This approach can be developed sequentially until ultimately activities on sub-critical paths must be considered. A point will ultimately be reached when, by no further reduction, duration can be achieved whatever the additional expenditure.

#### 4.4 The application of time cost models

To test and further develop the principles set out in Section 4.3 they are now related to a number of illustrative examples.

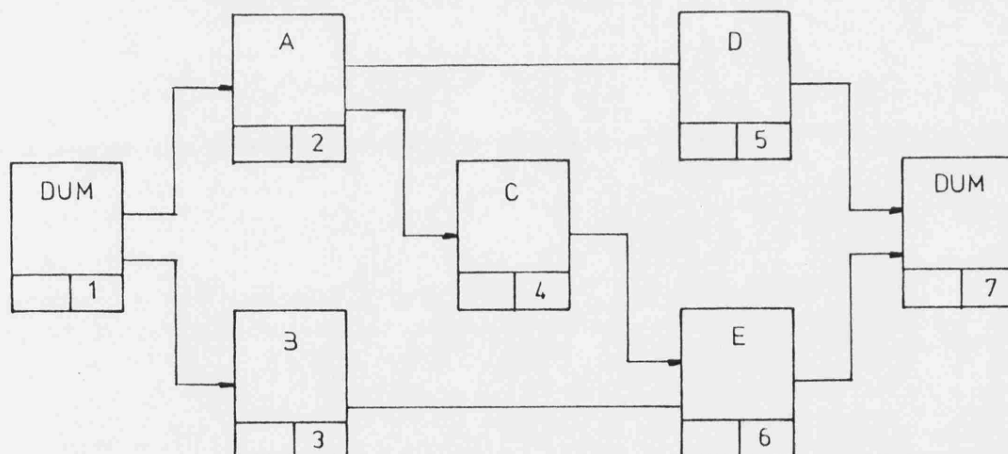


Figure 4.12

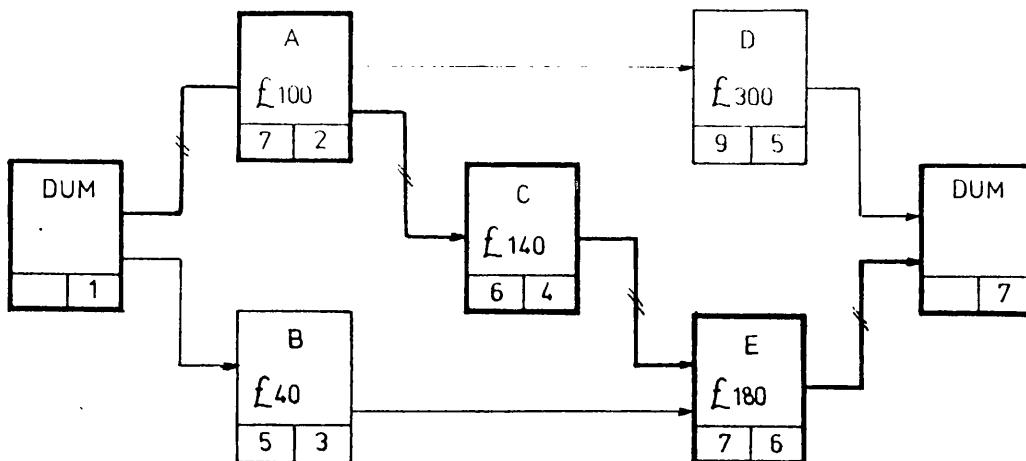
The network shown in Figure 4.12 represents a phase of a construction project. Details relating to Minimum Cost Duration, Crash Duration, Minimum Cost, Crash Cost and Slope are identified in Schedule

Activity DES	i-j	Mcd (weeks)	Cd (weeks)	Mc (£)	Cc (£)	Slope $\frac{Cc-Mc}{Mcd-Cd}$ £
A	2	7	4	100	190	30
B	3	5	4	40	80	40
C	4	6	2	140	280	35
D	5	9	6	300	390	30
E	6	7	3	180	360	45

Minimum Cost (Mc) - £760

Crash Cost (Cc) - £1330

Schedule 4.1

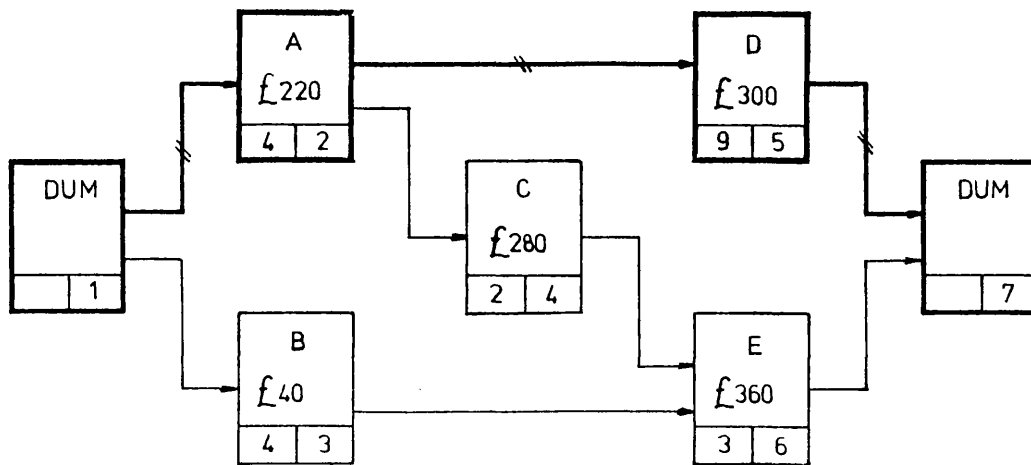


Total Cost £760 (Schedule 4.1). Total Duration 20 weeks.

Figure 4.13

In practice the client or the contractor himself might well wish to achieve an earlier completion date. Assuming a target duration of 13 weeks for this phase of the contract, there are several ways in which this target duration could be achieved. Three alternative solutions are suggested in Figures 4.14, 4.15, and 4.16.

Solution 1



Activity	Cost £
2	220
3	40
4	280
5	300
6	360
	<u>360</u>
Total Cost	<u>1200</u>

Figure 4.14

Total Duration - 13 weeks

Solution 2

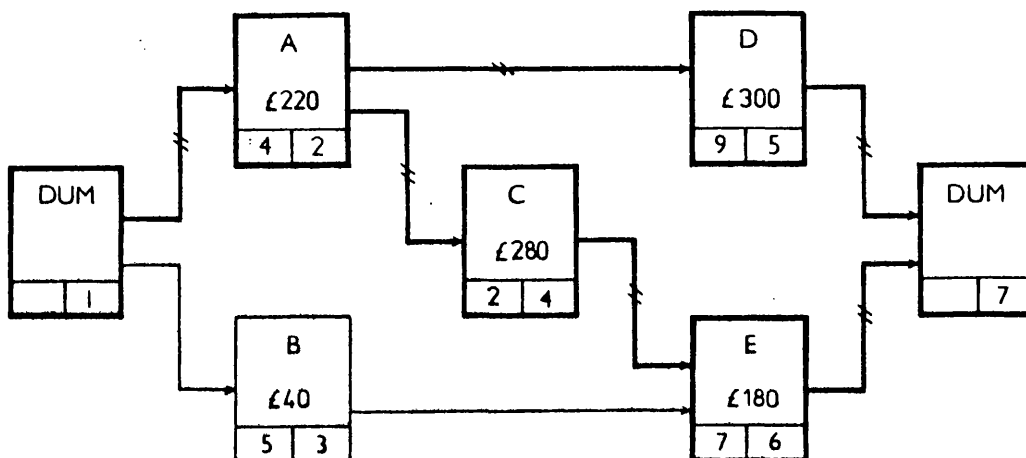


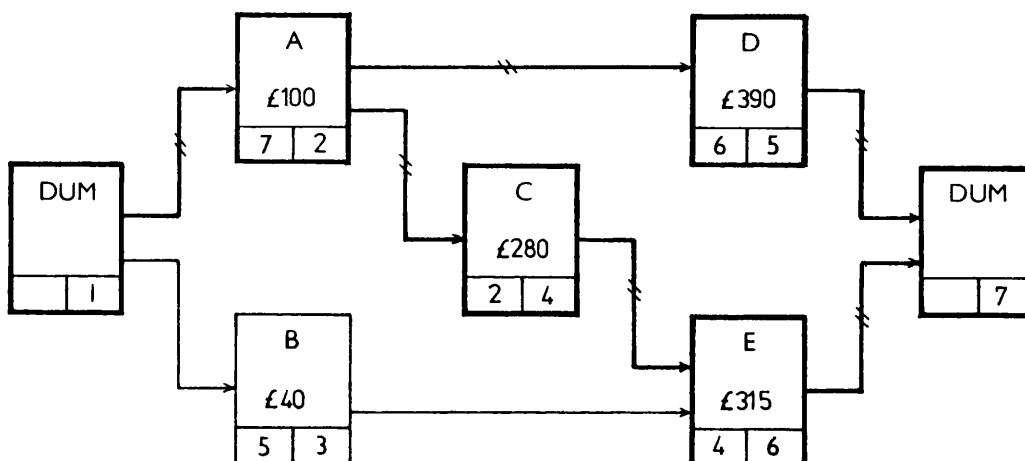
Figure 4.15 (contd)

<u>Activity</u>	<u>Cost</u>
	£
2	220
3	40
4	280
5	300
6	180
Total Cost	<u>1020</u>

Total Duration - 13 weeks

Figure 4.15

Solution 3



<u>Activity</u>	<u>Cost</u>
	£
2	100
3	40
4	280
5	390
6	<u>315</u>
Total Cost	<u>1125</u>

Total Duration - 13 weeks

Figure 4.16

It can be seen that these suggested solutions all satisfy the Minimum Cost Duration and Crash limits and all can be completed within the scheduled time scale of 13 weeks. Solution 1 has, in fact, changed

the critical path and Activity 6 has become critical. No reduction in duration has been achieved by crashing Activity 6 which was originally on the critical path, (Figure 4.13). However, Solution 2, by failing to reduce this activity at all has produced two critical paths. Solution 3 has produced two critical paths. Activity 6 has not, however, been reduced to its full Crash Cost. Each solution produces a different cost and in practice management would probably select the least costly as being the most acceptable.

The general situation relating to projects of this nature is illustrated in graphical form in Figure 4.17. Here durations have been plotted against their corresponding costs. It is clear that the costs will vary even for identical durations. The notation 'C' represents in ascending magnitude, the variable costs attributable to each duration. The lowest one on each axis is the least cost for that particular duration. If adjacent minimum cost factors are joined by a curve a function of duration costs versus duration is obtained. This function is referred to in this research as the Project Cost Curve. It can be seen from Figure 4.17 that only one schedule cost is plotted for the minimum cost duration and that for this project duration all activities are at their minimum cost condition. The Project Cost Curve shown in Figure 4.17 represents the lowest direct investment for that activity so that the sum of these figures represents the lowest direct investment for the project. This principle introduced in Section 4.3 is now further developed to consider the implications of an "all-crash" situation, i.e. a situation where all activities are described at their crash duration thus representing the highest direct investment for the project.

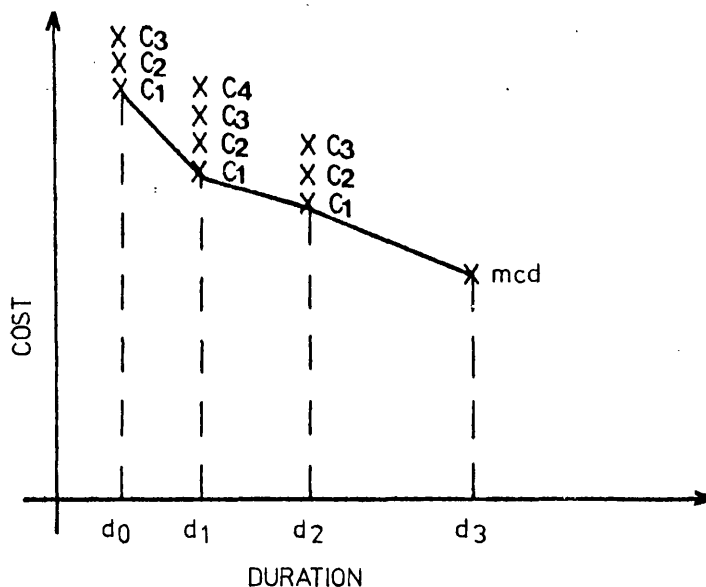
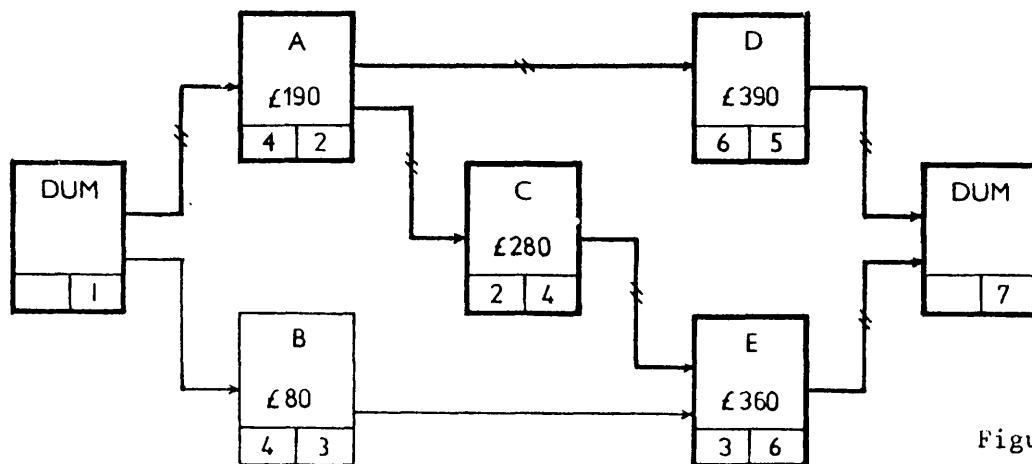


Figure 4.17

Figure 4.18 uses the information given in Schedule 4.1 to produce an "all-crash" situation.



Total Cost £1330 (Schedule 4.1)      Total Duration - 10 weeks

The Crash Duration (Cd) for this project is 10 weeks, i.e. it cannot be completed in less than 10 weeks in that no activity duration can be reduced further. It can be seen that activities 3 and 4 or 6 have float time and their durations could be increased by one week without influencing the overall project duration. In fact the additional investment incurred in crashing these activities has not influenced the overall completion time for the project. This illustrates the point made in Section 4.3 that it is not necessary nor in fact, economical, to expedite all activities to their crash position. By increasing the duration of the activities with float, a possible saving of £85 (6% of the total cost) may be achieved. This has, however, the disadvantage of making activities 4 and 6 critical. It can be seen that minimum project duration may be attained with a variety of activity investments and that detailed information on minimum investment is an essential facet of decision making.

It is shown in Chapter 5 that more information can be obtained about the cost curve than just its upward trend as the duration decreases, i.e. the cost curve is not just a straight line connecting minimum and crash costs. When intermediate costs are available, it is obviously desirable to make use of them and thus obtain a more precise cost curve. This type of data will probably be available where activities of a similar nature have been undertaken on previous projects. At the pre-tender or overall contract planning stages activities may well be broad in scope and therefore it would be inaccurate to plot only minimum and crash costs. Where more precise data exists curves of the type developed in 4.1 (e.g. Figure 4.19 shown below) can be established.



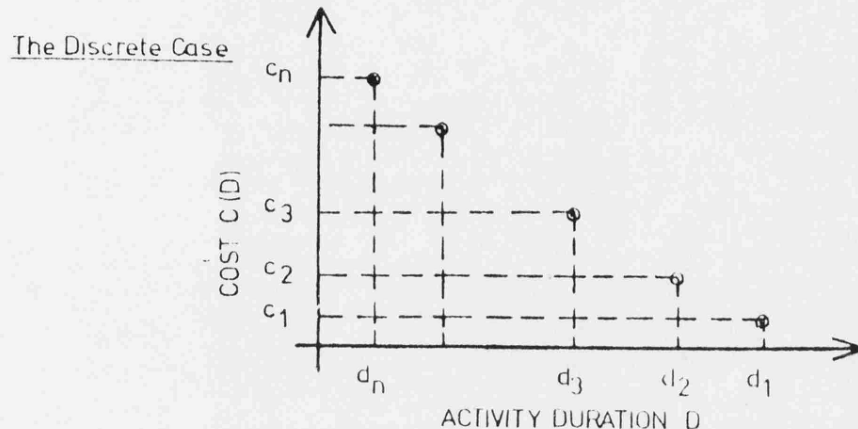


Figure 4.19

In this discrete case there are a finite number of possible durations.

As described in Figure 5.7 and 5.8, Chapter 5, further variations occur when the time cost curve is discontinuous in nature, i.e. one which is continuous over some intervals defined only at discrete points in other intervals and undefined in still other intervals.

It can be seen that the cost curve in Figure 4.19 is, in fact, represented by several small straight line segments. The crash duration, minimum cost duration, crash cost and minimum cost are shown at  $d_n$ ,  $d_1$ ,  $c_n$  and  $c_1$  respectively.

It is appropriate now to consider the problem of evolving the project cost curves identified in mathematical terms in Chapter 5. The first step is to produce a minimum cost schedule for project duration  $n_1$ . Then an alternative minimum cost schedule having a slightly different duration  $n_2$  must be determined. Any decrease in the project duration will naturally increase the cost of the project as a whole. It is essential therefore that the initial investment be as small as possible to ensure that the new programme is at minimum cost.

The problem of finding the minimum cost schedule for  $n_1$  project duration can be solved simply by allowing each activity in the project to be performed at its minimum cost duration. The second step is a little more complex and is best explained by reference to an example using the information shown in Schedule 4.2, which refers to a simple two activity project.

#### Schedule 4.2

<u>Activity</u>		<u>Mcd</u>	<u>Cd</u>	<u>Mc</u>	<u>Cc</u>	<u>Slope</u>
DES	No.					
A	1	5	3	100	150	25
B	2	7	4	50	185	45

In this example the minimum cost and minimum cost duration figures given in Schedule 4.2 are used to plot the project to a time scale, (Fig.4.20).

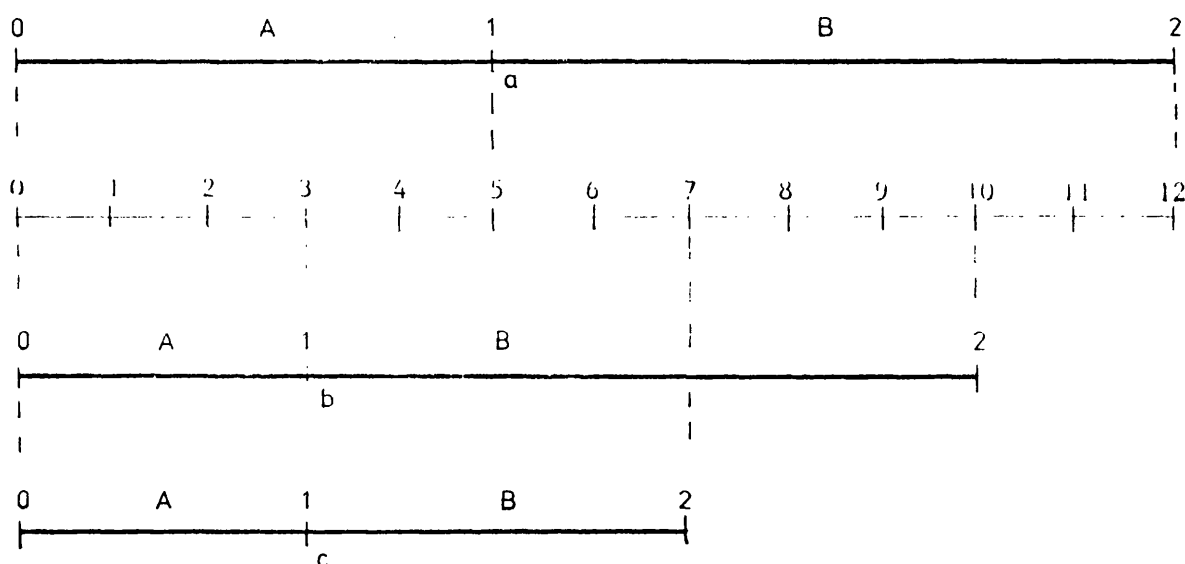


Figure 4.20

It can be seen that the overall duration for this project based on minimum cost duration is twelve time units, giving a total cost of £150. Any reduction in this figure would, of course, need to be accomplished in such a way as to minimise the additional investment involved.

Examining the slope for these two activities, it can be seen that the cost of reducing Activity A by one time unit is £25 whereas the comparative cost of reducing Activity B by one time unit is considerably higher, i.e. £45. It is obvious therefore that the minimal increase in overall cost would be achieved by crashing Activity A to its maximum (Fig. 4.20). By doing this the project duration has been reduced to ten time units with a corresponding increase in the overall cost of £200. An increase of 33.3%. To effect any further reduction in duration it is now necessary to consider Activity B.

The courses of action available are (i) to simply decrease Activity B by  $n$  time units or (ii) to increase Activity A by  $n$  time units, at the same time decreasing Activity B by  $n + 1$  .... time units. However, due to the differing slope values for these activities, any attempt to increase the duration of Activity A and correspondingly reduce the duration of Activity B would necessarily result in an increase in cost. Therefore, any further decrease in the overall duration - bearing in mind the need to minimise additional investment - can only be achieved by reducing the duration of Activity B. The limit of decrease occurs when Activity B has reached its crash limit, resulting in the situation illustrated in Fig. 4.20.

The project duration has now been reduced to its absolute minimum and therefore no further reduction is possible. In summary, the overall duration has been reduced from 12 to 7 time units, a reduction of 58% and the total cost has now increased to £335. An increase of 123%. In a sense, activity durations are decreased by applying "time pressure" to them. The higher the time investment cost required to effect a decrease, the more time pressure is required. In the situation illustrated in Fig.4.20 the first activity reduced in duration is the one with the least resistance, i.e. Activity A. When further pressure is applied and no further reduction is possible in terms of this activity, time pressure is then applied to Activity B until the crash limits for this activity are reached. It is not possible to effect any further reductions and the crash limit is therefore reached for the project as a whole. The project cost curve resulting from this time pressure is illustrated in Figure 4.21.

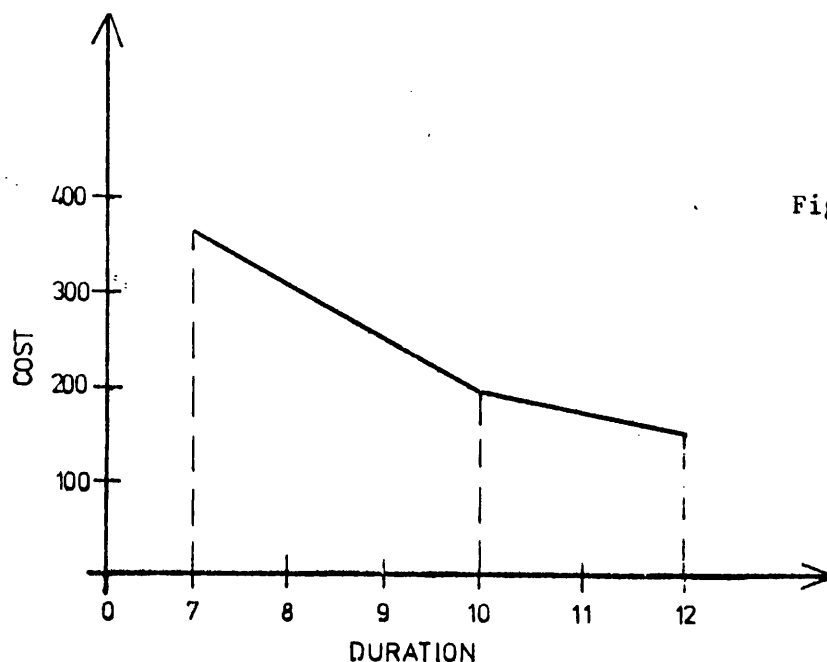


Figure 4.21

In that this problem contains only two activities it is comparatively simple to evolve a solution. As the number of activities increases however, the analysis becomes more complex. The difficulty relates to determining those activities that should be changed to ensure that the investment costs of a unit decrease in project duration, are kept to a minimum. Consider, therefore, the project data set out in Schedule 4.3. Using  $M_{cd}$  and  $M_c$  values the project is plotted as a time scaled network in Figure 4.22.

Schedule 4.3

Activity DES	No.	$M_{cd}$ (weeks)	$C_d$ (weeks)	$M_c$ (£)	$C_c$ (£)	Slope $\frac{C_c - M_c}{M_{cd} - C_d}$ £
A	2	7	4	100	190	30
B	4	5	4	40	80	40
C	3	6	2	140	280	35
D	5	9	6	300	390	30
E	6	7	3	180	360	45

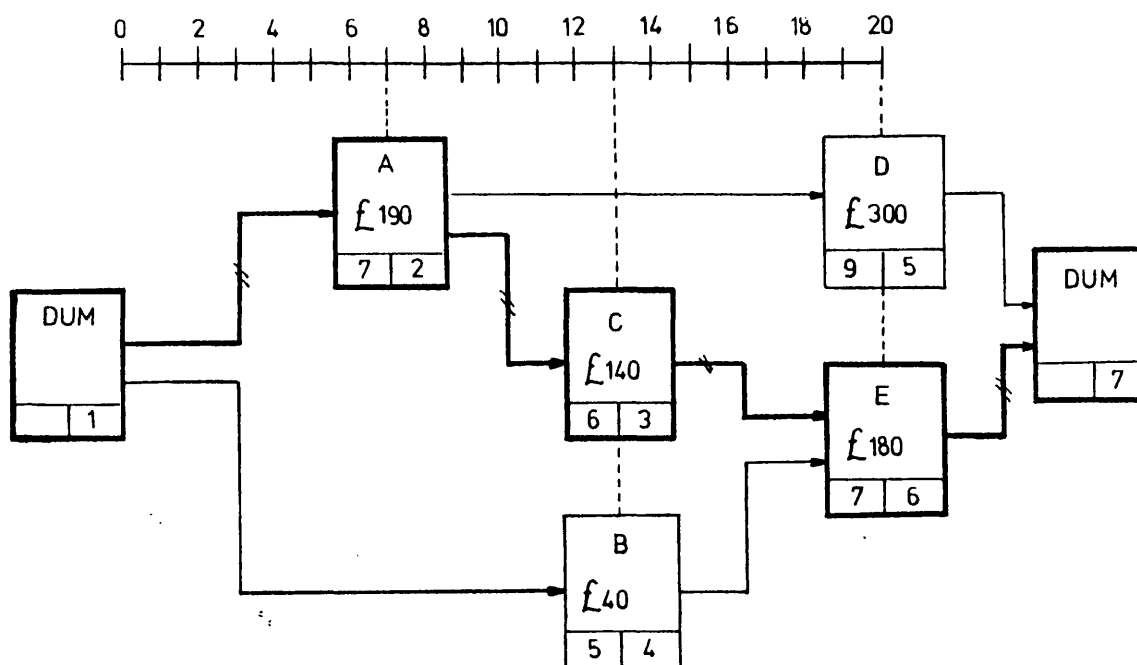


Figure 4.22

It can be seen from Figure 4.22 that the Critical Activities are A, C & E. As previously stated time pressure is applied first to the critical activities in a project commencing with the activity with the smallest resistance, i.e. the smallest slope cost. It can be seen that Activities B & D have float time available when the contract is operated at minimum cost duration. Examining the critical activities the cost slope is £30, £35 and £45 for Activities A, C and D respectively, thus Activity A has the smallest slope and would be considered first. It is useful at this point to consider the significance of "float" (see chapter 3), i.e. the spare time available for the completion of activities not on the critical path (non critical activities). There are two main types of float. Total Float, i.e. the float on an activity which can be used up without delaying the final completion date and Free Float, i.e. the float on an activity that can be used up without delaying the earliest start of any subsequent activity.

If the float available on non-critical activities is used up then these activities become critical, i.e. critical activities are those without float. Negative float cannot, of course, be tolerated and should such a situation occur management must take action to accelerate activities on the critical path or revise the logic of the project. Two other types of float may be identified, namely, independent and interfering float. These are seldom used for control purposes and are not considered in this research.

When an attempt is made to reduce the duration of a project a situation is often reached where more than one critical path evolves. If all activities in a project become critical then the situation becomes even more complex and all paths will become critical.

Even for a small project of the type illustrated in Fig.4.22 where one or two obvious solutions are readily apparent there are, in fact, a large range of variations possible involving the increase or decrease in the duration of the five activities concerned, each producing a different cost effect. In current practice however, it is the best intuitive solution that is normally adopted. This type of solution rarely takes into account the many alternatives available and does not present a sound basis for decision making.

Returning now to the project shown in Figure 4.22 the data provided can be used to prepare progressive duration cost information of the type shown in Schedule 4.4.

#### Schedule 4.4

Total  
duration  
(weeks)

	20	19	18	17	16	15	14	13	12	11	10
A	(7)	6	5	<input type="checkbox"/> 4	<input type="checkbox"/> 4	<input type="checkbox"/> 4	<input type="checkbox"/> 4	<input type="checkbox"/> 4	<input type="checkbox"/> 4	<input type="checkbox"/> 4	<input type="checkbox"/> 4
B	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)	(5)
C	(6)	(6)	(6)	(6)	5	4	3	<input type="checkbox"/> 2	<input type="checkbox"/> 2	<input type="checkbox"/> 2	<input type="checkbox"/> 2
D	(9)	(9)	(9)	(9)	(9)	(9)	(9)	(9)	8	7	<input type="checkbox"/> 6
E	(7)	(7)	(7)	(7)	(7)	(7)	(7)	(7)	6	5	4
Total Cost (£)	760	790	820	850	885	950	1015	990	1065	1140	1215

( ) Minimum Cost Duration (Med)

☐ Crash Duration (Cd)

Analysing the project progressively the smallest cost slope on the critical path is that related to Activity A and successive reductions can be made until the "crash" duration of four time units has been reached, thus reducing the overall contact period to 17 weeks at an additional cost of £90. Any further reduction in project duration must be achieved by progressively reducing Activity C (critical activity with lowest cost slope), until an overall project duration of 13 weeks has been achieved at an overall cost of £990. At this point however, Activity D has become critical thus creating two critical paths. It will be necessary to reduce both critical paths simultaneously. However, at this point Activity C has reached its crash limit therefore Activity E (crash slope £45) must now be reduced in duration. As there are now two critical paths Activities D and E must be considered simultaneously although their cost slopes are of different values. The minimum period in which this project can be completed is 10 weeks (Fig. 4.23).

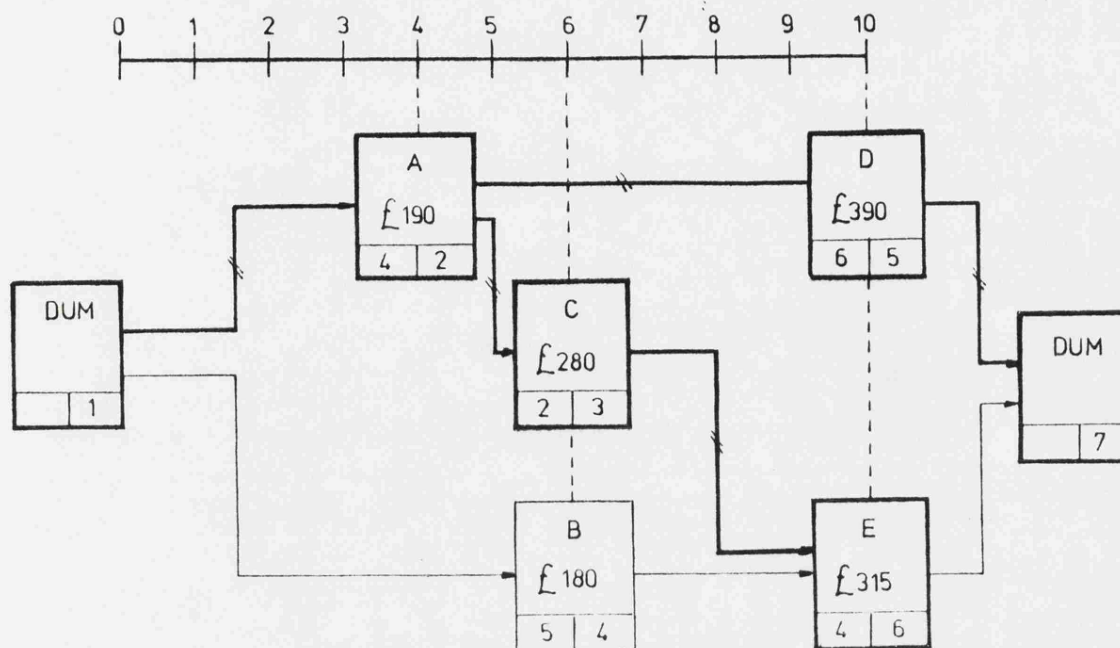


Figure 4.23

This has been achieved by crashing Activities A, C and D. Project control has become more complex as there are now two critical paths A, D and A, C, E. The overall cost has now risen to £1215. Activity E could be further reduced to its crash duration of 3 time units making it non-critical. This would not however, reduce the overall contract duration of ten weeks and would, of course, increase the overall cost by a further £45.

The project cost curve for this project is shown in Fig.4.24.

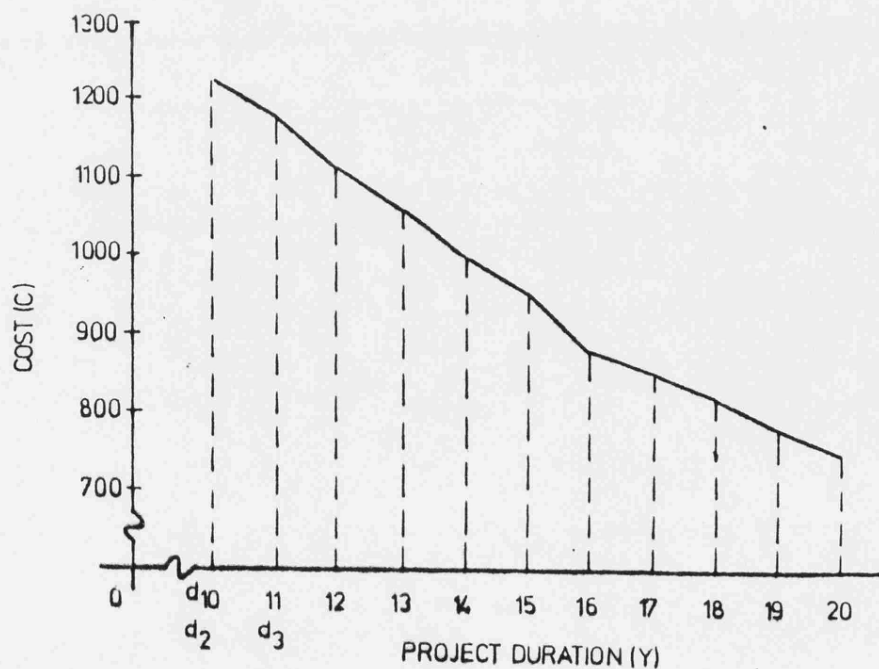


Figure 4.24

To determine the project cost curve it is necessary to produce a minimum cost schedule for a number of project durations. It is clear from this simple project that there are a variety of possible combinations and that it would be impossible to compute them manually for the highly complex set of activity relationships that exist in the normal construction project.

#### 4.5 Total Project Cost Curves

The previous sections have been concerned primarily with the direct costs, i.e. manpower, plant, and materials incurred in executing a project.

Indirect costs are, however, incurred on all construction activities and it will obviously be advisable to spend money up to these costs in order to reduce time. It follows that when the cost of reducing the duration of an activity or a complete project by  $n$  time units is greater than the indirect costs for that period then the total cost will rise.

Indirect costs relate in the main, to general administrative costs (see Chapter 3), and in the case of construction projects will also apply to such factors as penalties for not completing a project or some portion of it within a stipulated time period. Indirect costs may be particularly significant in situations where the early completion of a project will have a profound effect on the client's maximisation of his investment, e.g. completion of a factory designed to manufacture a new or more competitive commodity such as micro-computers. In this case the later the project is completed the smaller will be the client's short term or even long term share of the market. Factors such as these may be of considerable significance and may well warrant the crashing of a project even though the initial project cost is increased. In fact, in extreme cases the return on investment achieved by early completion may be greater than the total contract value. It is, of course, necessary to balance these factors in order to achieve an optimum return on investment, and therefore to identify an optimum or near optimum relationship between indirect costs and the duration of the project.

Indirect costs can be plotted in the same way as direct costs to give what is referred to in this research as the Indirect Project Cost Curve. In seeking to optimise this relationship both indirect ( $y$ ) and direct costs ( $x$ ) must be plotted to obtain a Total Project Cost Curve (Fig. 4.25). The Direct and Indirect Cost Curves are aggregated to obtain the Total Project Cost Curve. The time yielding the minimum investment costs or optimum costs occurs when the total project cost curve is at its lowest (A - Fig. 4.25). Where the



client requires early completion of the contract to maximise his investment, such as the case illustrated above, the loss to the client could be computed for each day the completion of the project is delayed and a Loss Function obtained. This function can now be added to the total project cost curve. It can be seen that the optimum project completion date occurs where the composite cost curve (z) is at its lowest (B-Fig.4.26) therefore at this point the return on the client's investment is maximised.

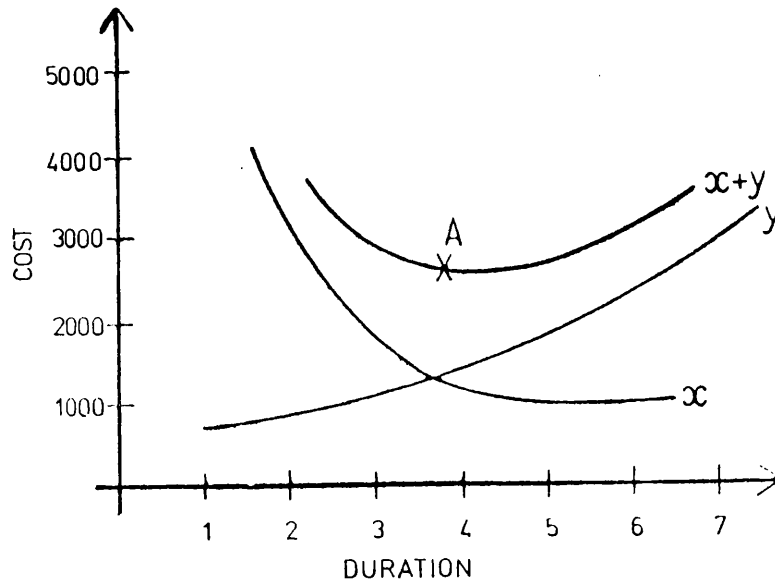


Figure 4.25

Conversely, in certain circumstances the contractor may be awarded a bonus for completion before the target completion date. This situation can also be accounted for in a similar way.

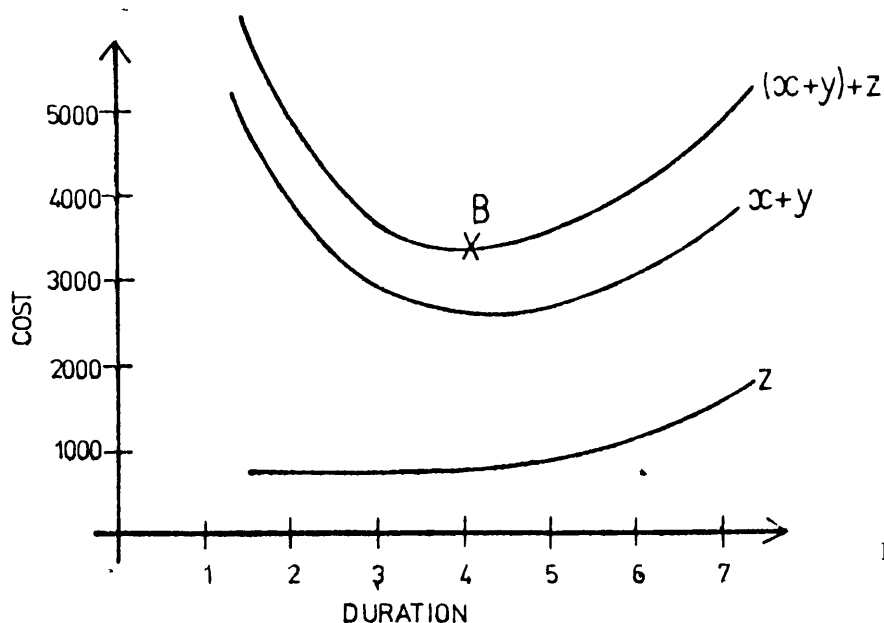
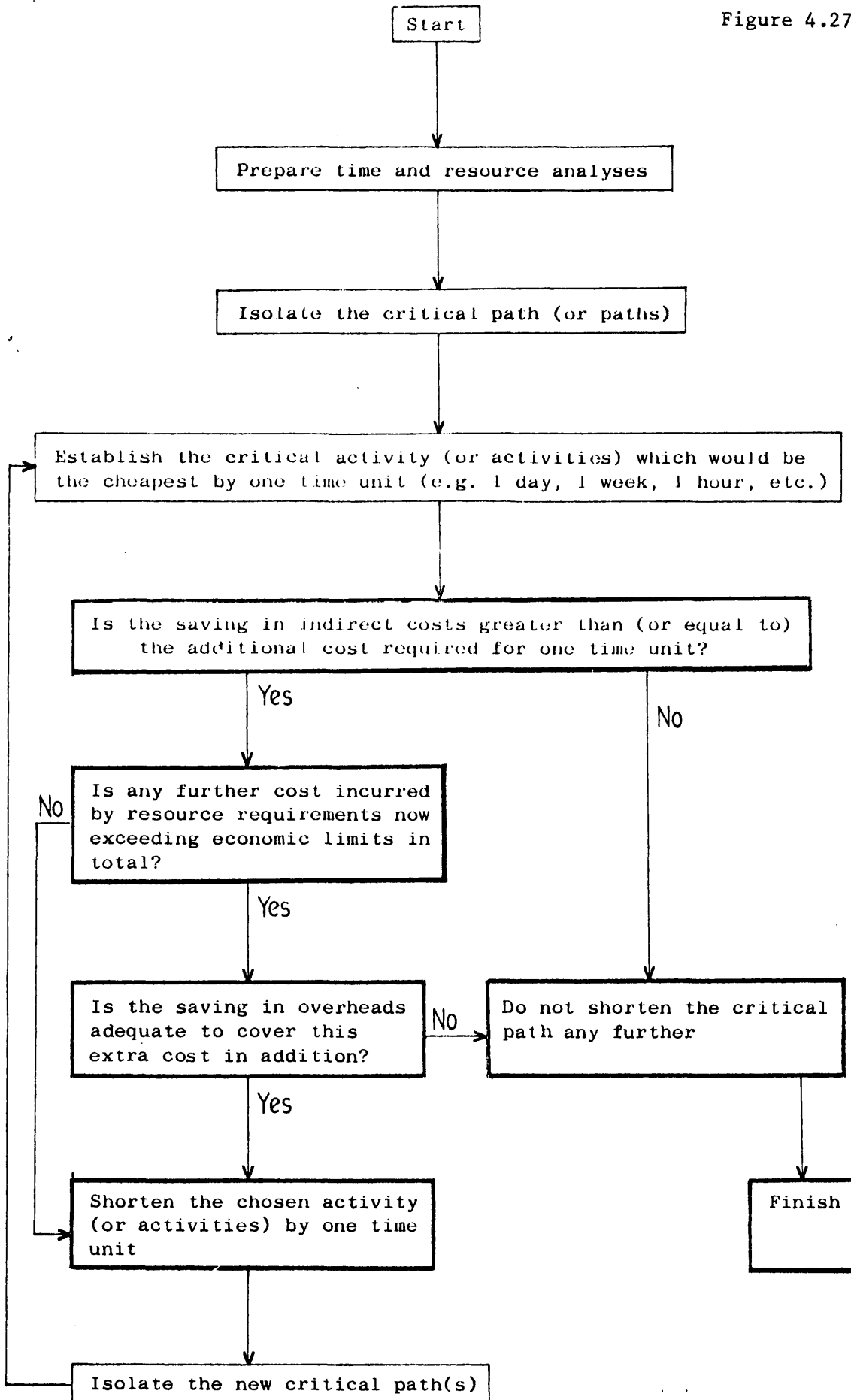


Figure 4.26

Figure 4.27



A flow chart suggesting a sequential procedure for reducing activity/project duration to obtain optimum time/cost relationships is shown in Figure This situation is developed further in Chapters 5 and 6.

Due to the difficulties identified in Chapter 3 the generally accepted linear representation of indirect costs is used in this research project. The assumption that indirect costs behave linearly was the one considered most appropriate (and realistic) by the sample companies. The models suggested in Chapter 6 do, however, allow alternative indirect cost curves to be included when more precise data is available.

#### 4.6 Modelling the time cost parameters

It can be seen from the preceding sections of this chapter that the relationship between time and cost is a complex one. The problem of optimising this relationship is even more complicated and earlier researchers have suggested a variety of models. (Section 4.7). Models are in a sense, an attempt to initiate a systems approach to problem solving and decision making. The aim is to try to capture the major components and interaction of a system. Having developed the model it is possible to obtain valuable insights into the behaviour of a system with possibilities of optimising its performance. The general problem of modelling time and cost is now considered and some of the conditions and limitations of the modelling process examined.

The objective is to find some way of demonstrating in dynamic and reasonably precise terms the way in which time and cost are interrelated and how the inter-relationship changes with the expansion or the diminution of the two parameters. The ability to capture and respond to the dynamic nature of the situation has been considerably enhanced by the advances in computer technology, particularly in terms of the relatively low cost and interactive nature of the micro computer. The significance of these advances are explored in this research.

In practice, planners and managers associated with the planning and control of construction projects tend to show a lack of appreciation of the dynamics of the construction situation, (this premise would, of course, be vehemently denied by practitioners), due perhaps in part to the fact that there is no appropriate facility available, capable of handling the dynamic interrelationship of the time and cost parameters. The modelling approach suggested in Chapters 5 and 6 in drawing together information on time and cost, demonstrating it visually and systematically, and allowing the user to interact through the medium of the micro computer, is designed to provide a realistic basis for decision making.

An absolute essential for modelling is that the data introduced is consistent and is not distorted by personal bias. Unlike a manual system the computer system will not pause to consider the accuracy of the information provided. A system of cross checking is obviously desirable and the manager must still be able to spot errors and this, among other things, will increase his confidence in the output from the system. Certainly, in designing the models suggested in Chapters 5 and 6, the discipline imposed in the modelling process forced a series of rethinks. The modelling process itself was continually identifying possible sources of data error that were not apparent initially thus, developing a dialogue between the data and the user.

The problem that is to be modelled, i.e. the optimisation of time and cost is defined in the earlier sections of the chapter and the limitations imposed by the process of modelling identified. If the solution is to be of value, the conditions and limitations of its use must be recognised and the variables clearly defined. The limits of use are those variables which are not accounted for, whether in whole or in part by the model itself.

The selection of variables for use with the model are governed by two major criteria. First the cost impact of each individual variable which will be of great importance. Minor cost carriers may be omitted, but it is essential that all major cost variables are included if this is at all possible. A basis for selection might be Pareto's law of distribution which suggests that 20% of the constituents of a system account for 80% of the cost. It is therefore, obviously essential to ensure that as much as possible of the 20% is represented in the model thus ensuring a reasonable element of accuracy.

Secondly, the effect of the inclusion of certain variables on the complexity of the model must be taken into account, ie, certain variables have to be included no matter how complex they make the model, whereas others may not be significant enough to warrant their inclusion if by so doing they make the model too complex, (See Section 5.4).

It is important to identify independent variables. Independent variables do not exist in their own right, but must be identified by the researcher, thus their value is whatever the researcher gives them and does not depend on the value of the other variables. It is sometimes better to combine two or

more variables to give a more accurate reflection of time cost than that obtained by using the variables independently. The objective time cost function must be derived in order to relate the variables and time cost function in equation form.

Once the model has been constructed it will have to be tested, (Chapter 6), before it can be put into use. The data used for testing should be different from that used in making the model to avoid inherent defects. The limitations of the data used must be clearly identified in that it is highly unlikely that complete accuracy will ever be achieved.

Two basic approaches have developed from the research, the first is concerned with the optimisation of individual activities, and the second with the optimisation of the contract as a whole.

In both cases relationships between activities and data on both time and cost have been simulated to allow the more complex situations to be analysed. In practice, of course, the accuracy of the data used will be the essential feature determining the value of the outputs. However, precise values will vary from contract to contract. Labour is perhaps the most difficult of the contractor's major resources in this respect. It must be appreciated that human behaviour varies considerably in differing situations and different individuals react differently to the same situations. It is well known that output can vary considerably from day to day and from person to person. It is important therefore, to take behavioural aspects into account accepting that labour outputs will vary. The data values used for testing the models suggested are therefore simulated and do not reflect any particular organisation, although every attempt has been made to use realistic data.

The situation in the case of plant is somewhat different in that levels of production can be assessed with a much greater degree of accuracy. Nevertheless, outputs can vary due to intangible factors that must be identified and allowed for. (Cusack<sup>48</sup>). Attempts to derive an accurate estimate of the plant required, can sometimes be confusing as the optimum will not always be a whole number, i.e. the result may appear as 2.5 concrete pumps, this must therefore be taken to the nearest whole number, if the required output is to be achieved. This may represent a substantial increase in cost but may be essential if the activity involved is a critical one. Cusack has shown that there is often not just one but a number of break even points when attempts are made to optimise the time cost relationship for major items of plant.

Materials are, to a large extent, selected by the designer of the building, but the contractor is required to handle, store and use them. Furthermore, the emergence of performance specifications may introduce a new slant, placing greater responsibilities on the contractor for initial selection of materials.

In conclusion, therefore, the modelling problem dealt with in this research is concerned with the interaction of several variables and in designing the models suggested in Chapter 5 it was necessary to:

- i. Determine the variable factors relating to the time and cost parameters in order to control and predict them.
- ii. Identify those factors that have a significant affect on these parameters.
- iii. Explore and/or hypothesise about the relationships between the time and cost parameters.
- iv. Using 3. build up a series of equations and inequalities into a model or models.
- v. Test the model, using a series of complex interrelationships between activities and variable time cost values.

It must be emphasised that a model can never be "true" in the absolute sense of the word, in that at best it represents a logical deduction drawn from an imperfect set of assumptions. It is essential therefore that anyone using the model must have a sound grasp of its structure and the assumptions on which it is based, as set out in the body of this research thesis.

#### 4.7 Existing Models

A wide range of papers have been published on both time and cost. Initially, critical path methods such as CPM and PERT concentrated primarily on the time parameter, Kelley and Walker<sup>50</sup> using CPM models while Malcolm, Roseboom, Clark and Fazar<sup>51</sup> developed the PERT model, primarily for the development of the Polaris missiles. A wealth of information was written meantime about costs, but very few attempts were made to produce formal cost models. A notable exception to this trend in the construction field can be found in the work of

Stone<sup>43</sup>, who modelled cost but saw time purely as an incidental feature of this parameter.

In the early sixties several attempts were made to determine direct project cost curves. Kelley<sup>50</sup> published a method for finding an optimal feasible schedule using the primal/dual algorithm for solving linear programs while Fulkerson<sup>57</sup> developed an alternative solution based on network flow computations. These solutions were extremely rigorous necessitating a highly efficient computational procedure available only on the most high powered computers. This was due, among other things, to the large number of variables involved bringing with it the risk of error. These models assumed bounded piecewise linear, continuous, convex and non-increasing functions and accordingly used standard linear programming methods for their solution. Construction activity cost curves however, regularly violate this assumption in that they may assume any form that is bounded and non-increasing, therefore the value of this type of model is extremely limited.

A more practical approach to the problem was modelled by Fondahl<sup>53</sup>. This was an approximate solution designed for manual analysis and computation. It requires the systematic manual ordering of a series of defined steps backed up by a variety of data schedules. This process is considered to be over simplistic, and time consuming, requiring frequent and laborious reference to the network. The variations and subsequent need for continuous updating on construction projects make it unsuitable for all but the smallest projects. It has, however, the advantage of being easy to follow and may therefore have some appeal in the modelling of smaller projects.

Meyer and Shaffer<sup>54</sup> used integer linear programming methods to handle more complex trade off functions for varying configurations of the cost curve. This approach suffers once again from the excessively high computing time required, due to the large number of variables generated. Even a small network (50 - 100 activities), may involve as many as 300 variables and 500 constraints. This is further exacerbated by the fact that a great deal of computer analysis is required to cast the problem in an appropriate form in the first place. The risk of error inherent in this approach is self evident and in addition the model also suffers from a possible lack of convergence. The Meyer and Schaffer model is further refined and developed in Chapter 5, where attempts are made to reduce the number of variables by concentrating the analysis on the points of breakthrough on the time cost curves

Butcher<sup>55</sup> used dynamic programming to solve certain aspects of the time cost problem. However, this approach can deal only with pure combinations of sequential and parallel links making it totally unsuited for modelling construction projects where the complex interrelationship and inter-dependencies of the activities are an integral feature of the problem. Robinson<sup>56</sup> later developed a multi-dimensional dynamic programming model for dealing with arbitrary (non-increasing) activity cost functions. This approach is considered to be even more impractical in that no general algorithm can be developed and the complexity of the model makes it virtually unmanageable for even a small project. It is noteworthy that the available documentation on this method makes no attempt to show how it could be applied even to a simple networking problem.

Some of the earlier PERT models were extended to include cost functions. They suffered, however, from a number of computational and analysis problems similar to those discussed above and in addition were further complicated by the inherent problems brought about by the probabilistic structure of the PERT time models discussed in Section 3.3.

Further discussion on the optimisation problem takes place in Chapter 5 where alternative models are developed using integer linear programming and a heuristic approach to modelling the time and cost parameters.



## CHAPTER 5. TIME COST MODELS FOR MULTI ACTIVITY PROJECTS

### 5.1 Introduction

Chapter 4 discussed the relationship between the duration time for an activity and the cost of performing it. This Chapter is concerned with modelling this relationship and determining minimum project costs associated with each feasible duration of a multi activity project. It is necessary, therefore, to determine which activities in a construction project should be expedited and by how much, to produce a given project duration with the minimum increase in cost.

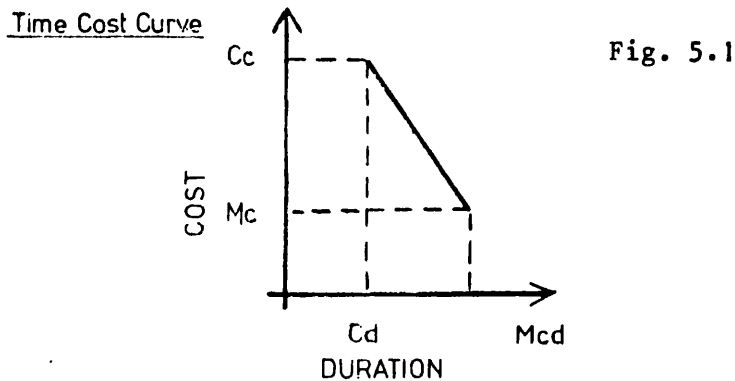
The problem is considered in four parts. The first part examines the problem of finding minimum project cost associated with given project duration, when the time cost relationship for each activity is only assumed to be continuous and totally defined in the feasible interval but not necessarily linear. A mathematical solution is explored relating the earlier work of Meyer and Shaffer<sup>54</sup>, based on integer linear programming, to the analysis of precedence networks. In the second part the methods of integer linear programming are also used to consider the more general problem of finding minimum cost for a project when for some of the activities the time cost relationship may only be partially defined. In the third part, the models in Parts 1 and 2 are consolidated and improved. It is argued that a time cost curve should be seen as a series of convex curves joined together by points of breakthrough. The fourth part highlights the disadvantages associated with the theoretical models developed in Parts 2 and 3 and suggests an heuristic approach to the problem. An algorithm is designed and the method of implementation using a 32K Commodore PET described. Detailed descriptions of the computer programs written for this purpose are included as Appendix 8, 9 and 10.

Consider first, three types of cost:

- i Indirect costs for the project as a whole, which depend on the project duration.
- ii Indirect costs for each activity, which depend on the activity duration.
- iii Direct costs for each activity.

Direct and indirect costs in the context of this research are defined in Chapter 2. It will be assumed that indirect costs, of Type 1 and 2 increase linearly with duration. Indirect costs of Type 1 are given by a project overhead expense per time unit. Indirect costs of Type 2 are given by associating an overhead per time unit with each activity.

Much of the earlier work in this field (Kelley<sup>50</sup> and Fulkerson<sup>57</sup>), assumed that direct costs for each activity decrease linearly (Figure 5.1) and therefore used linear programming to handle the problem. However, time cost curves attributable to construction activities often violate this assumption.



The points on the time cost curve shown in Fig. 5.1 are derived by determining the minimum cost duration (Mcd), the minimum cost (Mc), the crash duration (Cd) and its related crash cost (Cc). The relationship between the duration and the cost of the activity is then assumed to be continuous and linear between the defined end points of the curve. The algorithms developed by Kelley and Fulkerson used linear programming to model this type of problem. There are two basic assumptions:-

- i that the resources are not restrained in any way by the physical conditions of the activity.
- ii that the resource units are mutually independent.

In practice it is not always possible to combine alternative methods of completing a particular activity. Often the choice of one precludes the use of the other. Therefore, for this type of activity a continuous time cost trade off relationship cannot be developed. It is considered, therefore, that the assumptions relating to linear direct cost curves made by Kelley and Fulkerson are inappropriate for a high proportion of construction activities. Meyer and Shaffer<sup>54</sup> used integer linear programming methods to handle more complex trade off functions involving combinations of discrete points and continuous curves. Their solutions however, required the use of very large computing machines and even then were restricted to comparatively small networks with a maximum of 50 activities. Other disadvantages of this approach include the possible lack of convergence and due to the complex nature of the analysis, no method of measuring the optimality of the solution.

## 5.2 Minimum Project Cost when the Time Cost Relationship is continuous and totally defined in the Feasible Interval

Consider a project involving a large number of activities,  $A_1, \dots, A_N$ , which are interdependent in the sense that some activities cannot be begun until others are completed. The dependency relationship between activities is represented by a precedence diagram (Fig. 5.2)

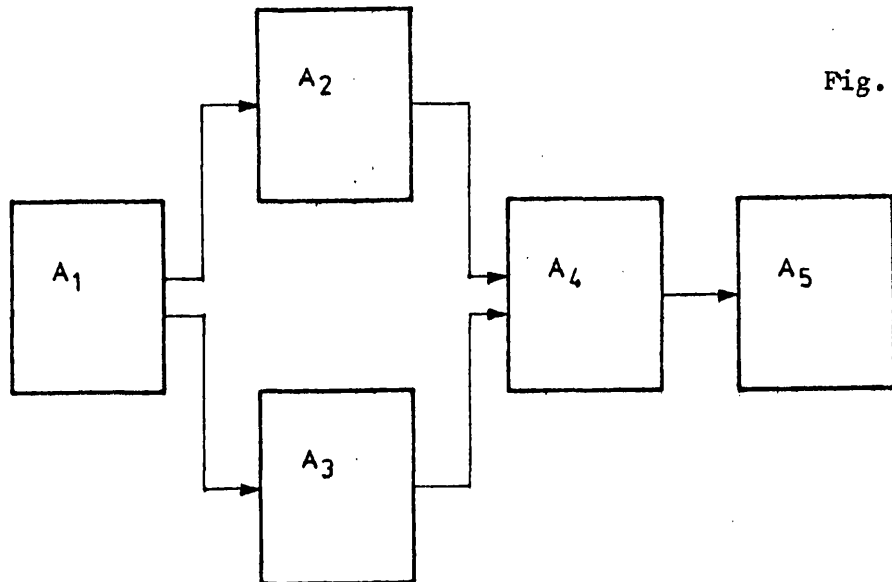


Fig. 5.2

In the precedence diagram the nodes are labelled with the names of the activities and an arrow goes from Activity  $A_i$  to Activity  $A_j$  if  $A_j$  cannot start until  $A_i$  has been completed. It is assumed that the overhead per time unit for the project as a whole is  $I$  and the overhead per time unit for Activity  $A_i$  is  $I_i$ .  $D_i$  is used to denote the duration for Activity  $A_i$ . The relationship between duration and direct cost for each Activity  $A_i$  is therefore some function of  $D_i$ ,  $C_i(D_i)$ . It is also assumed in this section that the functions  $C_i$  are continuous and totally defined between  $Mcd_i$  (the minimum cost duration), and  $Cd_i$  (the crash duration) for each  $A_i$ .

Given a schedule of durations for the activities, we can find the total direct cost of the project by taking the sum of the individual cost functions.

$$\text{Total direct cost} = \sum_{i=1}^N C_i(D_i) \quad \dots\dots\dots 1$$

The time,  $T$ , taken for the whole project is harder to compute since some activities cannot be started until others have been completed. The time  $T_i$  for completion of each Activity  $A_i$  is defined by sweeping forward through the precedence diagram.  $T_i$  is equal to  $D_i$  the duration of Activity  $A_i$ , plus the maximum  $T_j$  where  $A_j$  is a precedent of  $A_i$ .

$$T_i = D_i + \text{Max}(T_j : A_j \text{ precedent of } A_i) \quad \dots\dots\dots 2$$

The total time, T, taken for the project is then  $T_N$ , where  $A_N$  is the last activity.

The problem is as follows: For a given project completion time, T, choose activity durations  $D_i$  so that

$$T_N \leq T \quad \dots\dots\dots 3$$

$$\text{Total cost is minimized} \quad \dots\dots\dots 4$$

In order to state this problem in a linear programming form, equation 2 can be replaced by the set of constraints:

$$T_i \geq D_i + T_j \text{ where } A_j \text{ is a precedent of } A_i \quad \dots\dots\dots 5$$

The problem now is

$$\text{Minimize } IT_N + \sum_{i=1}^N C_i(D_i) + I_i D_i \quad \dots\dots\dots 6$$

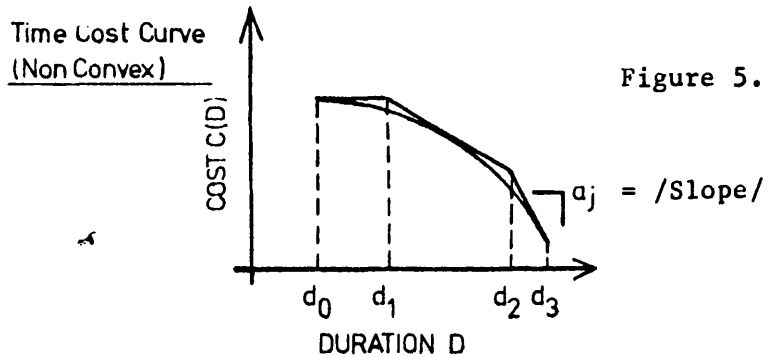
subject to the constraints

$$\begin{aligned} T &\geq T_N && ) \\ T_i &\geq D_i + T_j \text{ where } A_j \text{ is a precedent of } A_i && ) \quad \dots\dots\dots 7 \\ i &= 1, \dots N && ) \end{aligned}$$

### Linear Programming Solution

Given a precedence diagram, it is possible to derive inequality set (7) which is a set of linear constraints on the durations.

If the functions  $C_i(D_i)$  are linear, then this gives a linear programming problem which is solvable by standard methods. As previously stated it is not always realistic to assume that the time direct cost functions for all activities are linear. It is assumed in this section, however, that these functions are at least continuous, and they are therefore approximated by piecewise linear functions.



Any continuous curve can be approximated by a piecewise linear curve. The accuracy of the approximation depends only on the lengths of linear segment chosen. The piecewise linear approximation shown in Figure 5.3 can be expressed as:

$$C(D) = C(d_0) - \sum_{j=1}^3 a_j X_j \quad \dots\dots\dots 8$$

where

$$D = d_0 + \sum_{j=1}^3 X_j \quad \dots\dots\dots 9$$

$$0 \leq X_1 \leq (d_1 - d_0)$$

$$0 \leq X_2 \leq (d_2 - d_1) \quad \dots\dots\dots 10$$

$$0 \leq X_3 \leq (d_3 - d_2)$$

where  $X_1$  is the duration between  $d_0$  and  $d_1$   
 $X_2$  is the duration between  $d_1$  and  $d_2$   
 $X_3$  is the duration between  $d_2$  and  $d_3$

In general  $X_j$  is the duration between  $d_{j-1}$  and  $d_j$ .

As can be seen in Figure 5.3, a value of  $X_1$  that is less than  $(d_1 - d_0)$  is meaningless unless both  $X_2$  and  $X_3 = 0$ . Similarly if  $X_3$  is positive both  $X_1$  and  $X_2$  must be at their upper bounds. However, when  $X_1$ ,  $X_2$  and  $X_3$  are input into a linear programming model as separate variables the solution process forces the variables with the least cost slope to its upper bound before any of the other variables are allowed to enter into the solution, i.e. to become positive. In the activity time cost curve shown in Fig. 5.3 the solution process for a linear programme with an objective function to minimise cost would force the  $X_j$  to their upper bounds in a reverse sequence, i.e.  $X_3$  would reach its upper bounds first then  $X_2$  and finally  $X_1$ , making the whole exercise valueless. This does not, however, apply when the curve is convex, (Fig. 5.4).

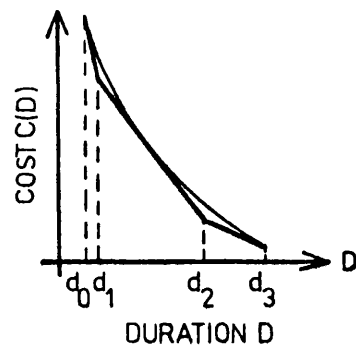


Figure 5.4

A solution to non convex curves was derived from the work of Markowitz & Manne<sup>58</sup> by Meyer & Shaffer, i.e. introduce integer variables  $\delta_1$  and  $\delta_2$  and add the conditions (11),(12),(13), to the previous example.

$$\delta_k = \text{non negative integer (0, 1, 2, ...)} \quad \dots\dots\dots 11$$

$$\frac{x_k}{d_k - d_{k-1}} \geq \delta_k \quad \dots\dots\dots 12$$

$$\delta_k \geq \frac{x_{k+1}}{d_{k+1} - d_k} \quad \dots\dots\dots 13$$

for  $k = 1, 2$ .

Since  $x_k \leq (d_k - d_{k-1})$  by condition (10), condition (12) implies that  $\delta_k$  is either 0 or 1. If  $\delta_1 = 0$ , then  $x_2 = 0$ , by condition (13). But (12) implies that if  $x_2 = 0$  then  $\delta_2 = 0$ . So there are just three possibilities for  $\delta_1$  and  $\delta_2$ .

$$\delta_1 = 0, \quad \delta_2 = 0$$

$$\delta_1 = 1, \quad \delta_2 = 0$$

$$\delta_1 = 1, \quad \delta_2 = 1.$$

When  $\delta_1 = 1$ , condition (12) implies that  $x_1$  is at its upper bound.

Similarly when  $\delta_2 = 1$ ,  $x_2$  must be at its upper bound.

When  $\delta_1 = 0$ , (13) implies that  $X_2 = 0$ . Similarly,  $\delta_2 = 0$  implies  $X_3 = 0$ . So there are just three possibilities for the sequence  $X_1, X_2, X_3$

$$0 \leq X_1 \leq (d_1 - d_0), X_2 = 0, X_3 = 0$$

$$X_1 = (d_1 - d_0), 0 \leq X_2 \leq (d_2 - d_1), X_3 = 0$$

$$X_1 = (d_1 - d_0), X_2 = (d_2 - d_1), 0 \leq X_3 \leq (d_3 - d_2)$$

In other words, conditions (11), (12), and (13), have had exactly the desired effect.

The general situation can be visualised by reference to Figure 5.5.

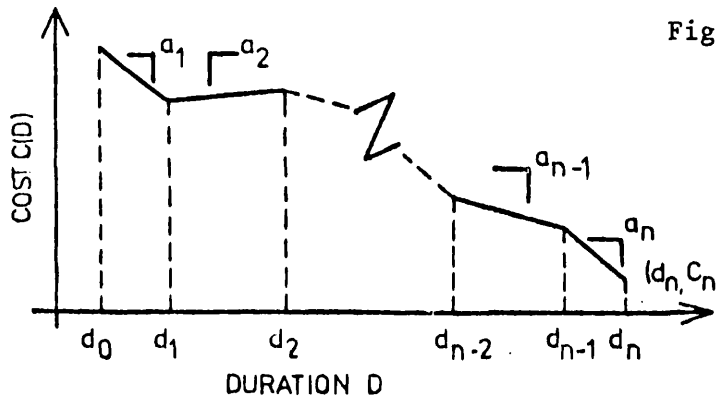


Fig. 5.5

We deal with this by generalizing the previously given equations.

$$f(D) = f(d_0) - \sum_{j=1}^n a_j X_j \quad \dots\dots\dots 14$$

$$D = d_0 + \sum_{j=1}^n X_j \quad \dots\dots\dots 15$$

$$0 \leq X_j \leq (d_j - d_{j-1}), j=1, \dots, n \quad \dots\dots\dots 16$$

$$\delta_k = \text{non negative integer}, k = 1, \dots, n \quad \dots\dots\dots 17$$

$$\frac{X_k}{(d_k - d_{k-1})} \geq \delta_k, k = 1, \dots, n \quad \dots\dots\dots 18$$

$$\delta_k \geq \frac{X_{k+1}}{(d_{k+1} - d_k)} \quad k = 1, \dots, r. \quad \dots\dots\dots 19$$

As before each  $\delta_k$  is restricted to the values 0 and 1, and  $\delta_k = 0$  implies  $\delta_{k+1} = 0$ . Also  $\delta_k = 0$  implies  $X_{k+1} = 0$ ; and  $\delta_k = 1$  implies that  $X_k$  is at its upper bound. Thus the values of  $\delta_k$  look like this:

1, 1, 1, ..., 1, 0, 0, ..., 0.

The corresponding possible  $(X_k)$  sequences look like this

$$(d_1 - d_0), (d_2 - d_1), \dots, (d_k - d_{k-1}), X_{k+1}, 0, 0, \dots, 0.$$

So conditions (14) to (19) satisfy the requirements of the problem.

Thus the central problem of minimizing cost while staying inside given project time,  $T$ , can, in principle, be solved in the following way:

Construct the precedence diagram for the project. Write down equations (6) and (7) by inspection of the precedence diagram.

Find piecewise linear approximations for the time cost functions  $C_1(D_1)$ . Then replace each piecewise linear approximation by the set of conditions given in (14), (15), (16), (17), (18), (19). Finally, the problem can be solved by using standard methods of integer linear programming.

### 5.3 Minimum project cost when the time cost relationship is only partially defined

The foregoing solves, in principle, the problem of finding minimum project costs in cases in which the time cost curve for each activity was piecewise continuous and totally defined in the interval between crash duration and minimum cost duration. In this section these methods are extended to consider the problems which arise when the time cost functions are only partially defined in this interval.

The initial problem relates to the case in which the time cost function is only defined at a finite number of discrete points (see figure 5.6). Consideration is then given to the case in which the time cost function is piecewise continuous as before but undefined on a finite number of intervals. This means that the time cost curve is like the one considered in the previous section except that the curve has been 'erased' on a finite number of intervals. This case is strictly more general than the previous one. The integer linear programming solution suggested by Meyer & Schaffer<sup>54</sup> is explored for this more general case, showing how the methods developed earlier in the chapter can be applied, thus giving a theoretical optimal solution.



# The Discrete Case

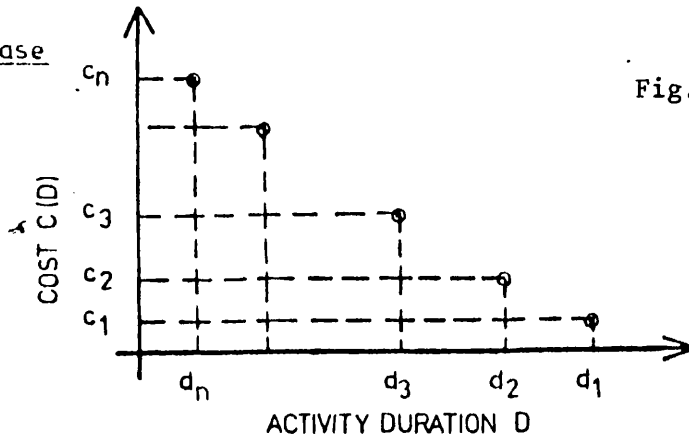


Fig. 5.6

In this discrete case, there are a finite number of possible durations,  $d_1, \dots, d_n$  and associated costs  $c_1, \dots, c_n$ . To take account of this situation, we define integer variables  $\delta_1, \dots, \delta_n$ . The objective is to require  $\delta_1$  to equal 1 if the duration is  $d_1$ ; otherwise  $\delta_1 = 0$ .

Assume the following conditions:

$$\delta_i \text{ is a non negative integer, } i = 1, \dots, n \quad \dots\dots\dots 20$$

$$\sum_{i=1}^n \delta_i = 1 \quad \dots\dots\dots 21$$

$$D = \sum_{i=1}^n \delta_i d_i \quad \dots\dots\dots 22$$

$$C(D) = \sum_{i=1}^n \delta_i c_i \quad \dots\dots\dots 23$$

Conditions (20) and (21) together imply that  $\delta_i = 1$  for just one value of  $i$ ; and for  $j$  not equal to  $i$ ,  $\delta_j = 0$ . Thus, in the sums  $\sum \delta_i d_i$  and  $\sum \delta_i c_i$  all the multipliers but one are 0. In other words, the only possibility is that  $D$  has one of the duration values and  $C(D)$  has the corresponding cost value. This means that the four conditions given define the time cost function.

Conditions (20), (21), (22), (23), can be set up for any number of discrete time cost functions. The resulting constraints can then be used in the framework described earlier to get a minimum project cost. Finding the solution therefore, involves integer linear programming.

It may also happen that the time cost function is defined as a continuous function over some intervals and also at a certain number of discrete points. Before solving the problem in general, consider first, three examples, viz. a discrete point followed by an interval of definition, Figure 5.7, an interval followed by a point, figure 5.8, and two intervals separated by an undefined region, figure 5.9

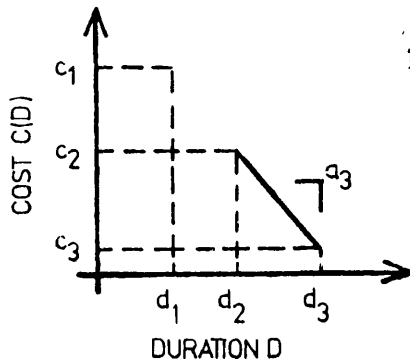


Fig.5.7

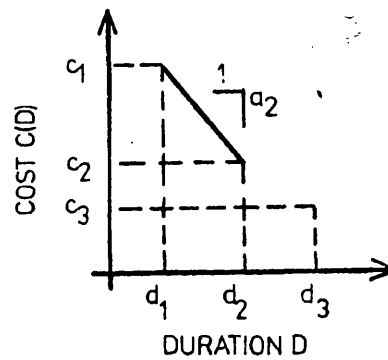


Fig.5.8

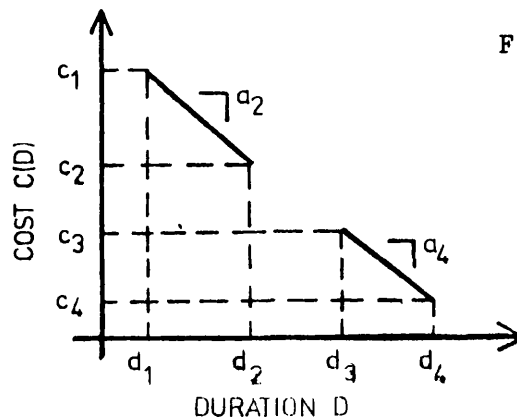


Fig.5.9

To model the situation shown in figure 5.7 where a discrete point is followed by a gap and then an interval of linear definition, it is necessary to introduce an integer variable  $\delta$ , which is to be 1 if the duration is  $d_1$ , and is 0 otherwise.

$\delta$  = non negative integer

$$0 \leq \delta \leq 1$$

Let  $D$  be the duration and stipulate

$$d_1\delta + d_2(1-\delta) \leq D \leq d_1\delta + d_3(1-\delta)$$

If  $\delta$  is 1, we have  $d_1 \leq D \leq d_1$ , so  $D = d_1$ .

On the other hand, if  $\delta$  is 0, we have  $d_2 \leq D \leq d_3$ .

So these conditions imply that the duration  $D$  is either in the interval between  $d_2$  and  $d_3$ , or equal to the discrete point  $d_1$ .

The cost can now be written as a linear function of  $D$  and  $\delta$

$$C(D) = (d_3 - D)a_3 + c_3 + \delta [c_1 - ((d_3 - d_1)a_3 + c_3)]$$

When there is an interval of definition followed by a discrete point as in Figure 5.8, an integer variable  $\delta$  is introduced which is to be 1 if the duration is  $d_3$  and is 0 otherwise.

$\delta =$  non negative integer

$$0 \leq \delta \leq 1$$

$$d_1(1-\delta) + d_3\delta \leq D \leq d_2(1-\delta) + d_3\delta$$

If  $\delta = 0$  we have  $D$  between  $d_1$  and  $d_2$ . If  $\delta = 1$ , then  $D = d_3$ .

As before the cost can be written as a linear function of  $D$  and  $\delta$ .

When there are two intervals of definition separated by an undefined region as in Figure 5.9 the duration  $D$  is written as  $X_1 + X_2$  and an integer variable  $\delta$  is then introduced to ensure that if  $X_2 > 0$  then  $X_1 = d_2$  and  $X_2 > d_3 - d_2$ .

$$d_1 \leq X_1 \leq d_2$$

$$0 \leq X_2 \leq d_4 - d_2$$

$\delta =$  non negative integer

$$0 \leq \delta \leq 1$$

$$d_1\delta + d_3(1-\delta) \leq X_1 + X_2 \leq d_2\delta + d_4(1-\delta)$$

If  $\delta = 0$  then  $X_1 + X_2$  is between  $d_3$  and  $d_4$ . On the other hand,

if  $\delta = 1$  then  $X_1 + X_2$  is between  $d_1$  and  $d_2$ . The cost can now be written as a linear function of  $X_1$  and  $X_2$ .

In all the above examples, the method adopted provides certain linear constraints involving integer variables which imply that the duration is confined to the appropriate domain.

The cost, which is a linear function of the variables which have been introduced, can then be minimized subject to the constraints, using standard methods of integer linear programming.

The general case of partially defined piecewise linear functions is now considered. (Figure 5.10).

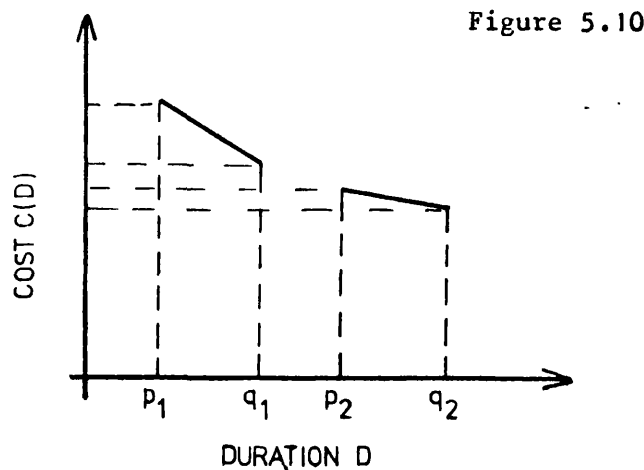
In this case  $C(D)$  is a piecewise continuous function with the added stipulation that the duration  $D$  must lie in one of a list of intervals.

$(p_1, q_1), (p_2, q_2), \dots, (p_N, q_N)$ , where  $p_1 \leq q_1 < p_2 \leq q_2 < \dots < p_N \leq q_N$ .

In other words, the condition

$$p_1 \leq D \leq q_1 \text{ or } p_2 \leq D \leq q_2 \text{ or } \dots \text{ or } p_N \leq D \leq q_N \dots\dots\dots 24$$

is added.



Since  $p_i = q_i$  may occur for some values of  $i$ , this case strictly included the previous discrete cases. To find a theoretical solution to the problem it is necessary to find a set of linear constraints which imply that  $D$  lies on one of the permitted intervals. Consider the following:

$$\delta_i \text{ is a non negative integer, } i = 1, \dots, N \dots\dots\dots 25$$

$$\sum_{i=1}^N \delta_i = 1 \dots\dots\dots 26$$

$$\sum_{i=1}^N \delta_i p_i \leq D \leq \sum_{i=1}^N \delta_i q_i \dots\dots\dots 27$$

The intention is that  $\delta_i$  should be 1 if  $D$  is in the interval  $(p_i, q_i)$  and otherwise  $\delta_i = 0$ . Conditions (25) and (26) together imply that just one of the numbers  $\delta_i$  can be 1 and the rest 0. Suppose  $\delta_j = 1$ .

Then

$$\sum_{i=1}^N \delta_i p_i = \delta_j p_j = p_j$$

$$\sum_{i=1}^N \delta_i q_i = \delta_j q_j = q_j$$

So condition (27) implies that  $D$  is in  $(p_j, q_j)$ .

Thus conditions (25), (26) together imply that  $D$  is in one of the permitted intervals. These constraints are added to the ones given previously in the chapter to achieve a theoretical solution.

#### 5.4 An alternative integer linear programming model based on points of breakthrough on the time cost curve

In this section the integer linear programming formulation of the problem is consolidated and improved. It is argued that the time cost curve can be described as a series of convex curves joined together by points of breakthrough thus reducing the number of variables and constraints to be considered. This hypothesis is developed below.

The subdivision of a project into activities can be undertaken at several different levels. In the first instance, most projects are broken down into readily identifiable construction activities. There is, however, a microscopic level below this at which these activities may, themselves, resolve into a set of sub-activities with a series of precedence relationships. There may also be a macroscopic level at which the project itself is seen as one activity or phase in a larger network (pages 133 & 134). It is reasonable therefore to expect that there will be a qualitative similarity between the overall project time cost curves and the time cost curves associated with individual activities. Therefore, whatever the level, the time cost relationship always displays a distinctive pattern and is never simply linear.

One of the distinguishing characteristics of direct time cost curves is that, commencing from the minimum cost duration it becomes progressively more expensive per time unit to expedite the project or activity. This characteristic continues until a certain breakthrough point is reached, at which point the cost increase drops dramatically and may even reduce to zero. Beyond this breakthrough point the cost of expediting the project again increases progressively until a further

breakthrough point is reached. A significant feature here is that for any particular time cost curve there are very few breakthrough points relative to the number of durations.

In mathematical terms, a direct time cost relationship can therefore be seen as a series of convex curves joined together by one or more breakthrough points. This corresponds with the general situation relating to an improvement in the performance of any activity, ie, improvement becomes increasingly difficult until a breakthrough point is reached. This can be illustrated by considering the learning curves associated with a physical skill where it is usually possible to identify a few significant points of breakthrough which establish a pattern for the complete process. Sometimes after a breakthrough point has been reached there is a discontinuous jump in the level of performance. This is reflected in the time cost curve by the flat portion immediately to the left of the breakthrough point (Fig. 5.11), i.e. areas of zero slope occur where a reduction in duration does not result in a corresponding increase in cost.

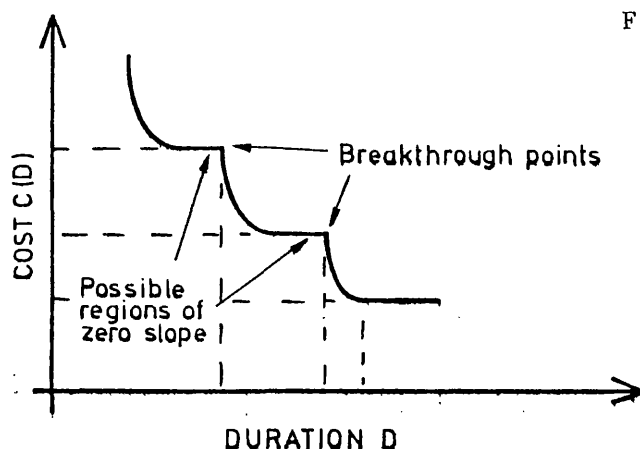


Figure 5.11

Project breakthroughs occur when there are discontinuous changes in the strategy for speeding up a project. Although a project breakthrough may occur when there is a breakthrough in a critical activity and consequently a radical shift in the critical path, in the majority of cases an activity breakthrough will not result in a corresponding breakthrough for the project as a whole. In a large project with several critical paths, an activity breakthrough will simply change the position of the critical path. Whatever method of time cost computation is adopted, it is inevitable that difficulties will arise in the area surrounding breakthrough points. This arises because the underlying situation at this point is basically unstable due to the fact that activity data near a breakthrough point is likely to be unreliable. Consequently, a slight change in the data will produce a radical change in the speeding up strategy for the project as a whole. This instability explains some of the difficulties encountered in the models

discussed earlier in the chapter and it accounts to a large extent, for the difficulties experienced by Meyer and Shaffer<sup>54</sup> in implementing their methods for other than the simplest networks.

An integer linear programming algorithm usually first approximates a solution assuming the time cost curves to be convex, and then looks for a series of small perturbations of the solution which make it consistent with the actual data. This applies when the underlying situation is stable. However, these small perturbations introduce possible cycles of errors when the underlying situation is unstable. This problem can be reduced by confining the analysis to the points of breakthrough. This assumption is now explored and presented as an alternative model to those suggested earlier in the chapter.

Assume first that only integral duration values are of importance. The data for an activity direct time cost curve is given by specifying costs for a finite number of integral duration values and points of adjoining durations are then connected by straight lines.

Suppose the direct cost remains undefined at some point on the curve, say  $d$ , which is between the crash duration and minimum cost duration. Select the greater value  $d_i < d$  at which the cost is defined. Let the cost at  $d_i$  be  $C(d_i)$  then define  $C(d) = C(d_i)$ . This can be done for every point  $d$ . In effect, the gaps in the curve are filled in with horizontal lines.

For every duration  $d_1, \dots, d_n$  there is then an associated cost slope  $a_1, \dots, a_n$ . The number  $a_i$  is the direct cost of reducing  $d_i$  to  $d_i - 1$ . The point  $d_i$  is a breakthrough point if  $a_i < a_{i+1}$ . Let  $b_1, \dots, b_B$  be the breakthrough points. The number  $B$  of breakthrough points is expected to be much smaller than  $n$ , the number of pieces in the piecewise linear curve, (Figure 5.12).

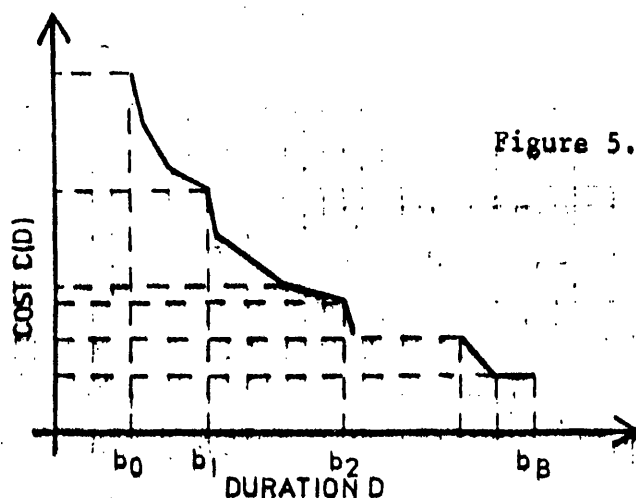


Figure 5.12

Let  $S_j$  be the amount of time reduction which has occurred in interval  $(d_{j-1}, d_j)$ .

$$0 < S_j < (d_j - d_{j-1}) \quad \dots\dots\dots 28$$

Let  $Mcd$  be the minimum cost duration and let  $Mc$  be the minimum cost.

If  $D$  is the duration and  $f(D)$  is the cost,

$$D = Mcd - \sum_{j=0}^n S_j \quad \dots\dots\dots 29$$

$$f(D) = Mc + \sum_{j=1}^n a_j S_j$$

For each breakthrough point,  $b_k$ , introduce a non-negative integer variable,  $\delta_k$ ,  $k = 1, \dots, B$ .

For each of these variables there will be two constraints. Consider a particular breakthrough point  $b_k$  and associated variable  $\delta_k$ . Assume

$$d_L = b_{k-1}$$

$$d_M = b_k$$

$$d_N = b_{k+1} \quad (\text{See Figure 5.13})$$

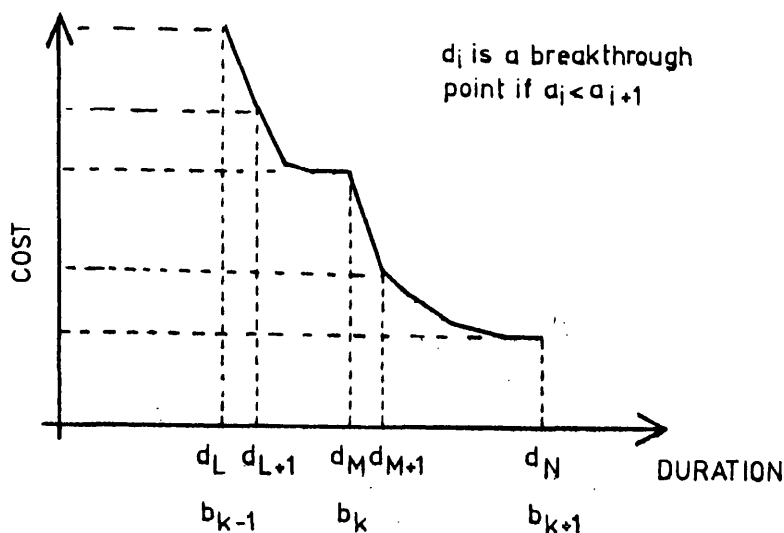


Figure 5.13

It is necessary to require  $S_{L+1} + S_{L+2} + \dots + S_M = 0$  unless  $S_{M+1} + S_{M+2} + \dots + S_N = (b_{k+1} - b_k)$ , which is its upper bound. The two constraints needed are

$$S_{L+1} + S_{L+2} + \dots + S_M < \delta_k (b_k - b_{k-1}) \quad \dots\dots\dots 30$$



$$\delta_k(b_{k+1} - b_k) < S_{M+1} + S_{M+2} + \dots + S_N \quad \dots\dots\dots 31$$

Unless  $S_{M+1}, \dots, S_N$  are all at their upper bounds, (31) forces  $\delta_k$  to be 0; and then (30) requires  $S_{L+1}, \dots, S_M$  to be 0.

Let  $S_1, \dots, S_n$  be the sequence of duration variables. It is claimed that linear programming will reduce these in the correct order. For each  $j$ , if  $d_j$  is not a breakthrough point, then  $a_j > a_{j+1}$  and thus an integer linear programming technique will automatically set  $S_j = 0$  until  $S_{j+1}$  is at its upper bound. (This is because  $S_{j+1}$  is cheaper than  $S_j$ .) On the other hand, if  $d_j$  is a breakthrough point, the constraints (30) and (31) require  $S_j = 0$  until  $S_{j+1}$  is at its upper bound.

A systematic method can now be given for setting out the integer linear programming formulation for any project. In order to be specific, assume that the integer linear programming package of MULTICS is used. A convention of this package is that all variables represent non-negative integers, so constraints of non-negativity will not be explicitly stated below. Let  $N$  be the number of activities. Assume that the time cost curve for activity  $i$  has  $cl(i)$  linear pieces with end points  $d_{i,0}, \dots, d_{i,cl(i)}$ , and that the cost slope in  $(d_{i,j-1}, d_{i,j})$  is  $a_{i,j} \geq 0$ .

The method is as follows:

- i. Introduce variables  $S_{i,j}$  for  $i = 1$  to  $N$ ,  $j = 1$  to  $cl(i)$ . Variable  $S_{i,j}$  is the amount of speeding up done in the  $j^{th}$  piece of the time cost curve for activity  $i$ . For each variable  $S_{i,j}$ , there is one constraint

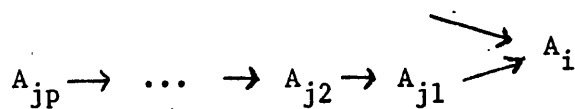
$$S_{i,j} \leq (d_{i,j} - d_{i,j-1}) \quad \dots\dots\dots 32$$

- ii. Starting with  $i = N$  and going back one step at a time to  $i = 1$ , do the following. If  $i = N$ , or if activity  $i$  has two or more precedents, introduce variable  $T_i$  to represent the completion time for activity  $i$ . Each variable  $T_i$  has as many constraints as the  $i^{th}$  activity has precedents. To be specific, if activity  $j1$  is a precedent of activity  $i$ , there is a constraint of the form

$$T_i \geq D_i + E_{j1} \quad \dots\dots\dots 33$$

where  $D_i = d_{i,cl(i)} - \sum_{j=1}^{cl(i)} S_{i,j}$

is the duration of activity  $i$ , and  $E_{j1}$  is an expression for the completion time of activity  $j1$ . To find  $E_{j1}$ , follow the precedence diagram arrows backwards from  $j1$  until an activity is found with two or more precedents. Suppose the path is  $j1, j2, \dots, jp$ :



Then  $E_{j1} = D_{j1} + D_{j2} + \dots + D_{jp-1} + T_{jp}$

where  $T_{jp}$  is the completion time of  $A_{jp}$  and  $D_{j1}, \dots, D_{jp-1}$

are durations of activities  $A_{j1}, \dots, A_{jp-1}$ .

iii. If there are  $k$  breakthrough points in the activity time cost curves, introduce  $k$  variables  $\delta_1, \dots, \delta_k$ . For each such variable there will be two constraints of the form (30) and (31), as explained previously.

iv. The completion time constraint for the project is

$$T_N \leq \text{Target completion time.}$$

The cost function to be minimized is

$$McP + \sum A_{i,j} S_{i,j} + I_n$$

where  $McP$ , the minimum cost for the project, is the sum of the minimum cost for all activities, and  $I_n$  is the indirect cost of the project.

v. The indirect cost is defined by one constraint

$$IT_n + \sum I_i D_i - I_n < 0$$

Where  $I$  is the indirect cost per time unit for the project as a whole;  $T_N$  is the project completion time of the project;

$I_i$  is the indirect cost per time unit of Activity  $A_i$ ; and

$$D_i = d_{i, Cl(i)} - \sum_{j=1}^{Cl(i)} S_{i,j} \text{ is the duration of Activity } i.$$

The technique outlined above is suitable for programming, and a program has, in fact, been written in BASIC on a 32K PET which reads project data from a file for projects of up to one hundred activities and prints out the integer linear programming formulation. (See Chapter 6).

### 5.5 A Heuristic Approach

It is considered that the foregoing theoretical models based on integer linear programming present a realistic solution to the problem of optimising time and cost, (see Chapter 6). They do, however, have certain disadvantages when applied to a large construction project. Although the alternative model developed in Section 5.4 represents a distinct improvement on the earlier work of Meyer

and Shaffer,<sup>54</sup> particularly in relation to the number of integer variables involved, it still retains many of the disadvantages identified below in varying degrees.

- i. The preliminary analysis necessary to derive a set of constraints from the network and the time cost data for each activity is complex and laborious. The ability to undertake this type of analysis requires a level of skill and understanding that cannot normally be expected from the average user.
- ii. The computational process related to integer linear programming is inherently complex due to the large number of constraints and variables and thus a large computer is required to deal with this aspect effectively. This would not be in line with the aim of this research project in relation to the real values of micro-computers in terms of flexibility and cost.
- iii. Although sophisticated in its mathematical development, the model presented could be unreliable when - as is often the case - there are a large number of variables and constraints. This is due to the stochastic behaviour of the two random data input variables, the fact that they may or may not be stochastically dependent and the complex nature of the analysis being undertaken.
- iv. The potential industrial or professional user "will reject out of hand any over sophisticated mathematical model". This view was the general one emerging from discussions with the sample construction companies consulted and confirmed by research work undertaken by Arditi<sup>59</sup>.

While the above difficulties are not insurmountable (see also Chapter 6) it was decided that in order to increase the likely level of acceptance by industry/ professions and exploit to the full the real values of the micro-computer, an alternative solution should also be developed. In a sense it was considered justifiable to sacrifice ultimate mathematical rigour in favour of operational acceptability. This approach is substantiated by Bellman<sup>49</sup> who states that "the essential purpose in formulating many mathematical models is not so much to calculate numbers, which are in many cases of dubious value because of the lack of knowledge of some of the basic constants and functions involved, but rather to determine the structure of the solution" .

Further experimentation indicated that a heuristic approach to the problem on the lines suggested by Fondahl<sup>53</sup> would provide a less complex solution, by modifying the computational procedures involved and simplifying the output information generated. Such an approach would also give more insight into the overall "structure of the solution".

The method adopted by Fondahl<sup>53</sup> is, however, a manual one and therefore limited in application and, of necessity, slow in operation and difficult to update. In addition, it cannot deal effectively with complex non linear cost curves.

The algorithm that follows is designed to cope with problems associated with non linear time cost curves and take advantage of the computational and analytical skills of the micro-computer. It eliminates the laborious process associated with a manual examination of all the potential critical paths in a project inherent in the Fondahl approach. This is particularly significant as the number of possible critical paths normally increases exponentially with project size.

It also overcomes the disadvantages associated with the "directional" approach adopted in the Fondahl method, i.e. once an individual activity is speeded up during one of the stages of "crashing" the overall project, it remains speeded up although this may not subsequently be necessary. The algorithm allows an activity that has been speeded up to subsequently be relaxed in terms of time and cost, when it becomes non critical in terms of overall project duration. This facility is most important in that it eliminates the possibility of expensive resources being committed unnecessarily.

The problem, as previously stipulated, is to schedule the activities in such a way that the cost is minimal and the project finishes before a given time  $T$ . The heuristic approach is to schedule the project for minimum cost, and then successively speed up the project by one time unit. The advantages of this are:-

- i. It is only necessary to find an algorithm which expedites the project by one time unit.
- ii. The solution identifies the time cost relationship over a whole range of values and not just at one point.

#### A Heuristic Solution

The objective, given an acceptable solution to the scheduling problem for time  $T$ , is to find a solution for time  $T - 1$ .

The first essential part of the algorithm is to identify the critical activities. In this context an activity is said to be critical if a delay in it will delay the project as a whole.

Assume  $T_j$  is the current duration scheduled for Activity  $j$ , and that

$A_i \rightarrow A_j$ , that is Activity  $j$  depends on Activity  $i$ , only if  $i < j$ .

The first step is to sweep forward through the precedence network, defining  $C(j,1)$ , which may be interpreted as the time when Activity  $A_j$  is completed. If  $C(j,1)$  has been defined for  $I < J$  let

$$C(J,1) = T_j + \text{Maximum} \{ C(I,1) : \text{where } A_i \rightarrow A_j \}$$

that is,  $C(J,1)$  is the time for Activity  $J$  plus the latest completion time for a precedent of Activity  $J$ .

The next step is to sweep backwards through the precedence network defining  $C(J,2)$ . This is the first time that a delay in Activity  $J$  is reflected in a delay for the project as a whole.

For the terminal Activity  $A_N$  we define  $C(N,2) = C(N,1)$

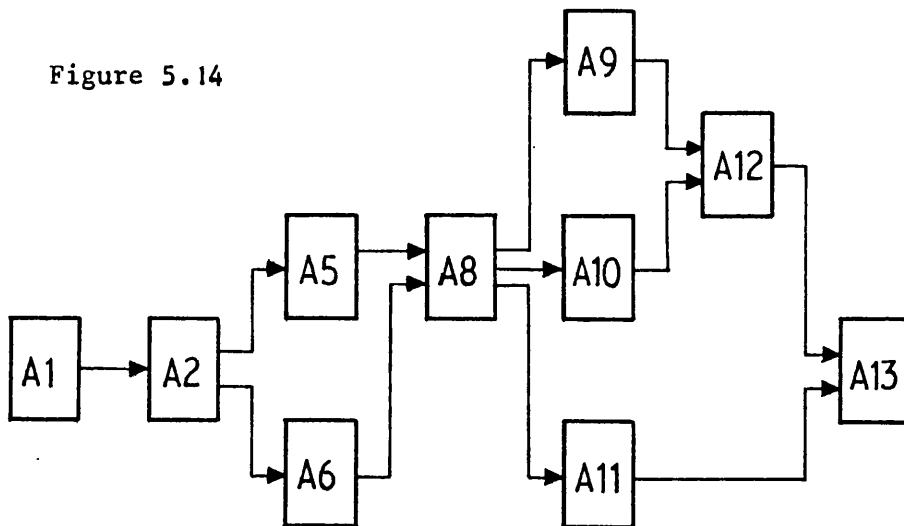
If we have defined  $C(I,2)$  for  $I > J$ , we let

$$C(J,2) = \text{minimum} \{ C(I,2) - T_I : \text{where } A_J \rightarrow A_I \}$$

Activity  $A_j$  is critical if  $C(J,2) = C(J,1)$

In the context of this research, the multiplicity of a critical Activity  $A_i$  is defined as the minimal number of activities in a set of critical activities including  $A_i$  which might be speeded up in order to decrease the project duration.

Figure 5.14



Considering the critical network shown in Figure 14, Activities  $A_1$ ,  $A_2$ ,  $A_8$ , and  $A_{13}$  have multiplicity one because a decrease in their duration immediately changes the project duration.  $A_5$  and  $A_6$  have multiplicity two because both have to be changed to expedite the project.  $A_{11}$  and  $A_{12}$  also have multiplicity two,  $A_9$  and  $A_{10}$  have multiplicity three because the minimal set containing  $A_9$  or  $A_{10}$  to speed up the project would be:

$$\{ A_9, A_{10}, A_{11} \}$$

There is nothing to be gained by speeding up non critical activities, therefore, only the critical activities are considered. When a critical activity is speeded up there are just two possible results:-

- i. The total project time is decreased, or
- ii. The speeded up activity, and every other activity on its branch of the critical path is taken off the critical list.

If a critical activity has multiplicity one, then speeding up that activity will result in speeding up the project as a whole.

Suppose Activity  $A_j$  has multiplicity  $N > 1$ : then speeding up  $A_j$  will not change the project duration. In order to expedite the project,  $A_j$  must be speeded up in conjunction with  $N - 1$  other activities. For this reason the cost of speeding up these other  $N - 1$  activities must be estimated. To this end an additional cost estimate  $E(J)$  is defined.

Suppose  $A_i \rightarrow A_k$ ,  $A_i$  and  $A_k$  are critical and  $j$  is between  $i$  and  $k$ . Then  $A_i \rightarrow A_k$  constitutes part of a critical path which goes around  $A_j$ . Let  $P$  be the critical path from  $A_i$  down to the first downward branch in the critical network. Let  $M_i$  be the minimum cost of speeding up an activity on  $P$ .

If all the activities on  $P$  are already at crash duration,  $M_i$  is set to be  $C(N + 1)$  where  $C$  is the cost of speeding up  $A_j$  and  $N$  is the number of times  $A_j$  has been relaxed.  $E(J)$  is then the sum of every such  $M_i$ .

Consider, for example, Figure 5.15.

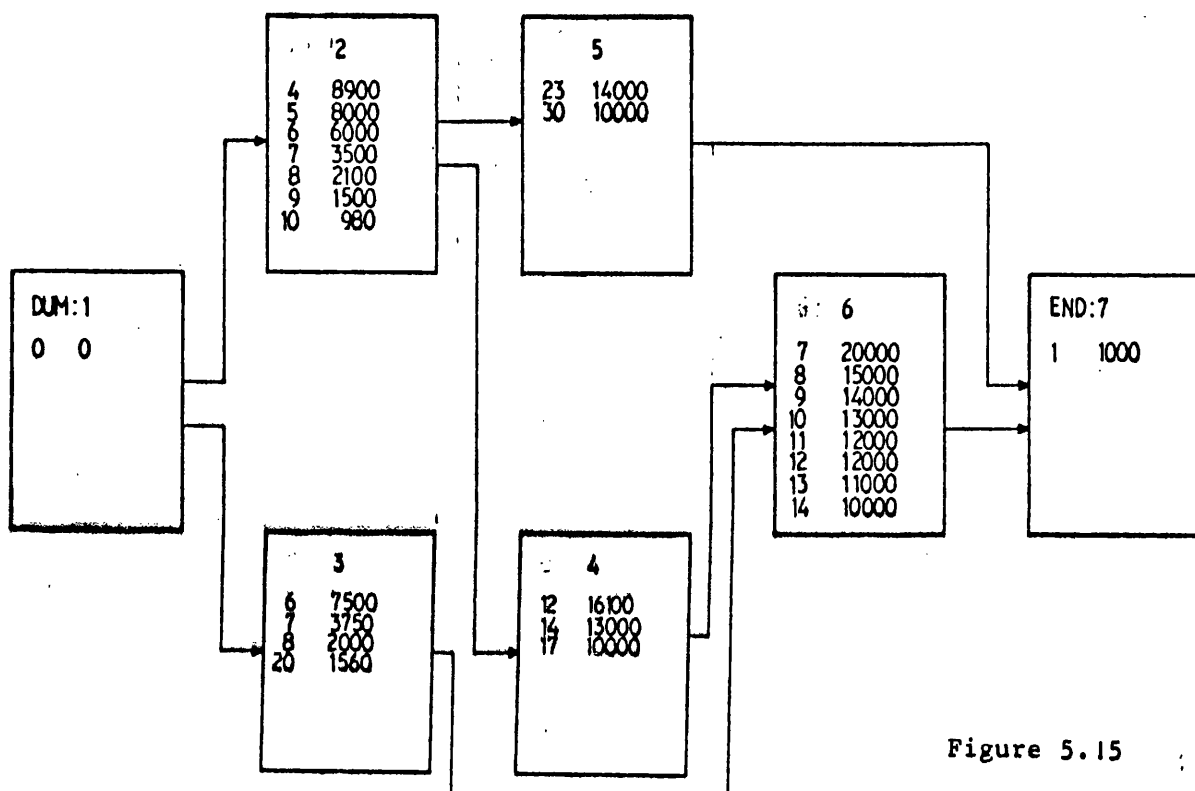


Figure 5.15

Suppose Activities 1,2,4,6 and 7 are critical. Then all critical activities have multiplicity one and  $E(J) = 0$  for all  $J$ . On the other hand, if 1,2,4,5 6 and 7 are critical, Activities 4,5 and 6 would have multiplicity two.

$$A_2 \longrightarrow A_5 \quad \text{so } E(4) = \text{Minimum} \left\{ \text{cost of speeding up } A_1 \text{ or } A_2 \right\}$$

which is £520 if  $D_2 = 10$ .

$$A_4 \longrightarrow A_6 \quad \text{so } E(5) = \text{Minimum} \left\{ \text{cost of speeding up } A_1 \text{ or } A_2 \text{ or } A_4 \right\}$$

which is £520 if  $D_4 = 17$  and  $D_2 = 10$ .

$$A_5 \longrightarrow A_7 \quad \text{so } E(6) = \text{Minimum} \left\{ \text{cost of speeding up } A_1 \text{ or } A_2 \text{ or } A_5 \right\}$$

which is £520 if  $D_5 = 30$  and  $D_2 = 10$ .

A succinct description of the algorithm can now be given.

- i. Sweep forward.
- ii. Sweep backward.
- iii. Define project duration, cost and critical activities.
- iv. Speed up critical Activity  $A_j$  where  $E(J) + \text{cost of speeding up } A_j$  is minimum.
- v. Repeat steps 1, 2, 3 and 4 until the project duration has been decreased by one time unit.
- vi. Relax, i.e. slow down, a non-critical activity by one time unit, if possible.
- vii. Repeat steps 1, 2, 3, and 6 until all non-critical activities are at a minimum cost.

#### Implementation of the Model

The problem requires that the precedents and a time cost function are determined for each activity. The data for the project therefore has the form:-

(Precedents for  $A_j$ , Time Cost function for  $A_j$ )

$j = 1, 2 \dots N$ , where  $N$  may be quite large

This information will be held on disc and read by the computer program (Chapter 6).

Allowance is made in the programs for up to 10 precedents for each activity and it is assumed that most of the time cost curves are approximately linear.

More precisely, it is assumed that at least 90% of the activities have piecewise linear time cost curves with no more than three pieces and that the remaining 10% have time cost curves which can be defined by a schedule of costs for a maximum of 50 consecutive durations.

Discussions with the sample construction companies suggest that these percentages represent a realistic balance for the majority of construction projects. It was also considered that for a high percentage of activities, only minimum cost and minimum cost duration data would be available,

So, for each activity there is a maximum of 10 numbers to record precedents, 8 numbers to record a 3 piece linear time cost curve, one number to record average cost, and the equivalent of one other number to record a description of the activity. Therefore, the equivalent of 20 real numbers is allowed for recording this basic data for each activity. In addition, provision is made to record up to 50 pieces of cost information for 10% of the activities. If N is the number of activities the amount of data can be estimated as:

$$(20 + 0.1 \times 50) \times N = 25N \text{ real numbers}$$

As discussed in Chapter 6, the program is designed to run on a micro-computer with  $\leq 32K$  memory space. Assuming 7 bytes for each real number, and 10,000 bytes for the program, the maximum number of activities which can be held at once in memory is

$$N = \frac{(32,000 - 10,000)}{25 \times 7} = \frac{22,000}{175} = 125$$

It is advisable to leave space in the program for additional data generated by the program itself, which would, in fact, be needed if it were necessary to refine or amend the algorithm. It seems reasonable, therefore, to expect the algorithm to deal with a maximum of 100 activities at any one time.

Construction projects may, however, be made up of thousands of activities. This situation can be handled in practice by sub-dividing the project into phases. The advantages of a planning/control time cost system that enables large projects to be subdivided into realistic phases, (coincidentally, about 100 activities was suggested as being appropriate) were highlighted in discussions with the sample construction companies. Each phase is given, perhaps arbitrarily, an initial activity and a terminal activity. No activity dependent on the phase can start until the terminal activity is completed. The program can be run for a single phase in isolation and the result will be a time cost curve for that phase. This phase can then be represented as one activity with an overall time cost curve, produced by the algorithm. As long as the difference between the crash duration for the phase and the minimum cost duration is less than 50 time units, this process can be repeated, and in this way the theoretical size of project that can be handled is unlimited.

The problem of subdividing a large project into phases is of course, a management one and not one that can be solved by the computer.

The interdependence of phases (Figure 5.16) may be linear or tree-like, or possibly, even more complex.



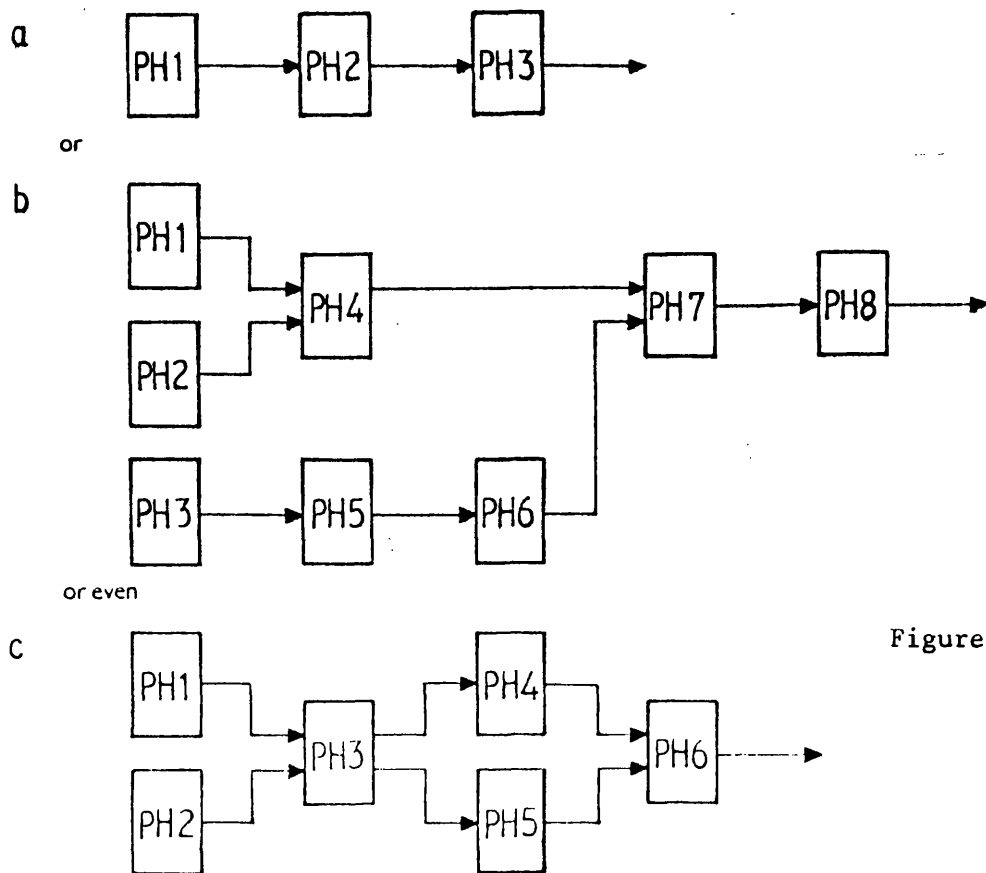


Figure 5.16

Considering Figure 5.16a the program for Phase PH1 could be run in isolation, and a time cost curve obtained. Phase PH1 can then be considered as one large activity, and joined to Phase PH2. The program will produce a time cost curve for the project up to the end of Phase PH2. The process is then repeated for Phases PH3, PH4 ----- PHN.

Considering Figure 5.16b, the program would first be run for Phases PH1, PH2 and PH3 in isolation. Phases PH1 and PH2 could then be considered as large activities and joined to Phase PH4. Continuing in this way a time cost curve can be produced for each phase of the project.

In the case illustrated in Figure 5.16c, the interdependence of the phases is not tree-like and the finishing times for Phases PH4 and PH5 are not independent since both depend on Phase PH3. It is not possible, therefore, to run through the project from beginning to end, substituting activities for phases. However, the program can be run for Phases PH4 and PH5 in isolation. A time cost curve can be obtained for Phase PH5. Now Phases PH4 and PH5 can be considered as large activities and amalgamated with Phase PH6. The phase interdependence is now tree-like and so the previous methods can be applied.

The testing, evaluation and implementation of the models are discussed in detail in Chapter 6.

# Main symbols used in Chapter 5

$A_i, A_j$	The $i$ th and $j$ th activity respectively
$A_i \rightarrow A_j$	$A_i$ is a precedent of $A_j$
$I$	Indirect Cost per time unit for the project as a whole
$I_i$	Indirect Cost per time unit for Activity $A_i$
$D_i$	Duration of Activity $A_i$
$C_i(D_i)$	Cost of Activity $A_i$
$T_i, T_j$	The duration from the beginning of the project until Activity $A_i$ or $A_j$ respectively are completed
$T_N$	Project duration
$D, C(D)$	Duration and cost for typical time cost functions
$X_j$	Duration Variable
$\delta_i, \delta_j, \delta_k$	Non Negative Integer Variables
$d_0, d_1, d_2, \dots, d_n$	Intermediate durations
$a_1, a_2, \dots, a_n$	Slopes of appraminating linear pieces
$C_0, C_2, \dots, C_n$	Costs associated with $d_0, d_1, \dots, d_n$
$S_{i,j}$	The amount of speed up of Activity $i$ on the $j$ th time interval.

## CHAPTER 6. THE TESTING, EVALUATION AND THE IMPLEMENTATION OF THE TIME COST MODELS USING A MICRO COMPUTER.

### 6.1 Introduction

This chapter looks initially at the development of computer based production systems highlighting the problems of planning and controlling the production process manually. The general resistance to the use of computers in the construction industry, particularly on site, is explored.

Sections 3 and 4 describe the micro computer hardware selected for use in the research and the software designed to implement the time cost models postulated in Chapter 5.

The final section describes the methods used to test the models considering, in addition to the quality of the solution, such features as computational efficiency and the need to adequately reflect real world complexities and constraints.

### 6.2 Development of a Computer Based Production System

On all construction projects, there are large and varied amounts of data available, much of which relates to the time and cost parameters.

Effective use of this data is severely inhibited by an inability to handle it effectively. To be of real use, it must be converted quickly and accurately into information systems, relevant to the production process as a basis for decision making. In practice, the managers who make the decisions rarely create the data, much of which is historical in nature and generated away from the construction site. A large volume of detail and irrelevant information which cannot be comprehended is of very little value to busy site managers.

The planning and control of production is a relatively complex process and is dependant on the availability of a large amount of timely information. When manual systems are used, the information is often received too late and, in addition, is often inaccurate. In practice, the analysis necessary for extracting the relevant information cannot be undertaken due to lack of time and resources. In this situation, it is often difficult or even impossible to detect the underlying reasons for major variations in levels of performance until it is too late to take corrective action. It is also difficult or impossible to update the initial plan to show accurately the current and planned activity state of a particular project, thus increasing the need for very close control and frequent expediting of critical items. To achieve this manually, it would be necessary to employ a large number of progress chasers and updating planners. This is not possible on

construction sites and even if it were economically feasible it would still be difficult to continually prepare, update and present project plans and reports as an effective aid to decision making. It would also result in a vast amount of paper work circulating on the site and between different sites and head office. The situation that emerged therefore, from discussions with the sample companies, was one of obsolete data and information that was of little or no value to the Site Manager.

It is not possible to cope manually with the time cost relationship presented in this research, other than for the smallest projects, (Fondahl<sup>52</sup>) for the reasons discussed above.

One turns naturally to the electronic computer to satisfy these defects in the information system leading to decision making in that it can:

- i. Digest vast quantities of data and perform many calculations in a very short time.
- ii. Process and analyse data far more accurately than manual methods and can be programmed to check itself for error.
- iii. Free management and other staff from time consuming, repetitive and often boring tasks allowing them to concentrate on critical activities.

Several studies have been undertaken relating to the use and development of computers in the construction industry, the most notable, although undertaken over a decade ago, being those by the Ministry of Public Building and Works<sup>61</sup> and Loughborough University of Technology<sup>62</sup>. The former study was directed at the use of the computer while the latter gave more emphasis to development work. It is not the intention to reiterate the findings of these reports. However, the following factors that emerged from the MPBW<sup>61</sup> report are worthy of note:

"For all but the smallest programmes the computer provides the cheapest method of carrying out time analysis of networks."

"The next phase of development of programming techniques must combine time and money."

"Due, however, to the volume of data to be processed and the very short time permitted for preparation ... etc., centralised batch processing techniques are unlikely to solve the scheduling problem."

The research undertaken by Loughborough University was basically a "WHICH" report, and provides little detailed information for the "user". It is of interest to note that although two of the programmes reviewed in this report included a form of cost analysis, viz. IBM, PERT/COST and ILSL - ICL1900 PERT, in neither case was the cost factor tested, neither is there any record of them having been used in practice.

A recent report by the National Consultative Council for the Building and Civil Engineering Industries recommended the formation of an independent association of computer-users to provide an advisory service and to develop industry-wide computing standards. As a result, the Design Office Consortium (DOC) was reconstituted and a report<sup>62</sup> published that provides impartial advice, particularly to new computer users. In addition the report provides an independent insight into the different tasks which computers are expected to perform in construction management.\*

In the context of this research, it is considered that the essential role of the computer in the production function is to capture and process data relating to a large number of activities which continually take place on site, highlighting deviations from planned operations or expected behaviour as a basis for management decision making. Computers in themselves do not, of course, make important decisions although routine decisions can easily be automated. All the important decisions have to be made by management. The computer is therefore, a tool which can be used to control production effectively and provide assistance to managers faced with a series of constant changes.

The objective, therefore, is to make the best use of the abilities as well as limitations of the two partners (computer and user), allowing the user to act in a flexible manner while utilising the ability of the computer to process and analyse at very high speeds, the large volumes of data which may be involved. It is, therefore, necessary to devise an effective man/machine relationship, particularly when an interactive mode of operation is to be used.

Initially the use of computer based planning and control systems forces managers to think, perhaps for the first time, about the methods currently in use, examining the logic and method of operation. Simply questioning the value and even the need for particular procedures can result in considerable improvements.

\* see also Bibliography Reference Nos. 65 & 66

The implications of particular conditions can be examined by simulating them on the computer and the results used to make feed forward control decisions instead of waiting for things to go wrong, in which case hasty decisions are often made. Such rash and intuitive decisions often exacerbate the existing situation producing bottlenecks in different areas at a later stage in the project. Use of a computer for such applications means that planners and site managers can devote an increased proportion of their time to thinking about policy decisions and control rules.

In practice, the availability of computer power will encourage management to review and revise its plans and policies on a regular basis. With manual systems, such reviews and revisions are carried out only infrequently, due to the large manpower resource required. When manual systems are in use decision rules frequently tend to be ad hoc and over a period of time an unconscious drift away from the formalised procedures takes place.

In addition to planning and controlling longer term aspects of the programme, computerised scheduling procedures are particularly valuable in setting and controlling daily working schedules on site. Quick assessment of an immediate situation can be undertaken allowing management to take rapid corrective action. The design, development and implementation of a computer based planning control system is extremely difficult and has been inhibited in the past by the remote nature of central computing facilities. This problem is considered in Section 6. It is important to note that a poorly designed and badly implemented computerised production planning and control system is worse than a good manual system which is fully understood and accepted by all the employees concerned. It must be noted that the introduction of a computer on to a site does not by itself result in better management of resources or higher profits. Best results are obtained by ensuring that the concepts used for planning and controlling production are sound and fully understood by the people concerned. The key to success lies in the ability of planners and site managers to appreciate the problems that exist on a construction site, and use the computer effectively for carrying out required data manipulations. It is important to ensure that the design of control procedures is undertaken by or in collaboration with senior production management.

A computer application must be designed in such a way as to help the operating personnel to carry out the day to day duties and create an environment in which the manager bases his final decision on as much objective information as possible. It is a well known fact that a site

manager who is not fully convinced of the desirability of computerising a particular function will hold back his support and the resulting system, even at best, can only be a limited success. The potential users are familiar with their particular requirements and can make a substantial contribution to the development and implementation of a computer based planning control system provided that they appreciate the potential use of computers in their working environment.

The format in which the information is presented to the users on site is a factor of considerable importance. Several otherwise well conceived systems have failed due to the fact that the data processing results are in the form of lengthy and unwieldy print-outs. A busy manager does not have the time to spend in searching for and identifying potentially useful information which is dispersed through irrelevant data. It is essential therefore, that the system produces summary and exception reports in which the detail can be varied to suit the needs of the user. Site managers should have a detailed knowledge of the role the computer can play in the decision making process. If this is not the case and managers do not appreciate the potential of the computer then the effect will be to simply automate the existing manual procedures and the opportunity to streamline them will be lost.

The time cost models developed in Chapter 5 can only be applied effectively by using a computer based system. In designing the system suggested in the subsequent sections the following general criteria was adhered to.

- i. The system must meet the requirements of the potential users and the temptation to design and implement a sophisticated system which is not understandable must be avoided.
- ii. The system should make as much use as possible of the exception principle, highlighting deviations from expected behaviour, thus keeping the amount of routine information to an absolute minimum, although this must be available for checking if required. It must be borne in mind that the manager would not have time to interpret and analyse a large volume of information. Although the hard copy output should be available this should be reduced to a minimum and as much use as possible made of visual display units. It is important to produce different outputs to meet the needs of the various users, e.g., contract managers, planners, directors, who should be consulted as to the most suitable format.

- iii. The computer's electronic data processing system provides information only by transforming the data input. The accuracy of this information is dependent on the availability of pertinent data, which must normally be input in a specified format. It is important, therefore, that the technique used to enter the data is accurately described and it is necessary to have a general data validation procedure which will check and reject unsuitable information, ie, the system should request the operator to re-enter incorrect data items or enter missing data. It is important to ensure that existing data is not inadvertently destroyed when new data is entered.
- iv. The programme should be designed in such a way as to allow additional modules to be added at a later date. It is also considered desirable to relate production based computer systems to other aspects of the company's work. This is, however, difficult in practice, bearing in mind the limitations of, for instance, the Bill of Quantities for planning and control purposes and has been disregarded for the purposes of this research.
- v. The levels of skill, quality, potential and responsibility of the ultimate users should be taken into account, particularly in an interactive system such as the one suggested in this research, in that the user may have to retrieve information from the system and input new or modified information, as appropriate.

### 6.3 Computer Hardware and factors affecting Program Design

It was obvious from the outset, that modelling the time cost relationship was complex in analytical terms. In addition, large quantities of data were involved and it was clear that the storage, processing and retrieval of this data could only be achieved by the use of a computer.

Initially, the intention was to use the Polytechnic's main frame computer and/or the Multics link up with the University. However, initial discussions with the sample companies highlighted the resistance to large computers generally. By coincidence, the Department of Construction and Environmental Health was, at this time, considering the feasibility of using micro computers and as a result an BK PET Commodore MICRO COMPUTER was purchased. Experimentation showed not only that it might be possible to study the time cost relationship with this but that its low cost and its interactive application made it suitable for use on construction sites. It also



seemed to overcome, to an extent, much of the "resistance" engendered by large central computers and appeared to offer a number of advantages, viz:

- i. Low capital cost - no additional running costs are incurred for computer time, telephone charges, etc. Running costs are therefore very low and maintenance minimal. No maintenance was necessary at all on the system used in this research.
- ii. An "on site" computer would generally be treated as a fixed "overhead", therefore its cost does not increase with use - conversely the cost of a remote computer does increase with use.
- iii. The interactive "user friendly" image generated by this type of computer helps to breakdown resistance to computer usage.
- iv. The possibility of rapidly updating plans is appealing to a busy site manager faced with continual amendments and variations in design, resource availability and production schedules.
- v. Site Managers expressed the view that an on site micro computer would be personal to site management, ie, it would not be used by senior management to "beat them over the head" - allowing them to amend and control their own plans without interference.

It became apparent, at an early stage, that the 8K PET micro computer did not have sufficient capacity to cope with other than the smallest combination of activities. In addition the cassette method of storage was very limited in terms of speed and was generally awkward to use. As a result a 32K PET micro computer was purchased and the cassette system was replaced at the same time by a dual drive floppy disk system. The complete system used in the research is comprised of a CBM 32K micro computer (Model 3032), a CBM Dual Drive Floppy Disk system (Model 3040) and a CBM High Speed Printer (Model 2023). This system proved capable of dealing with the full requirements of the heuristic model described in Chapter 5. As can be seen from the following schedule the total cost of the complete system was only £ 2140.

CBM 32K Micro Computer (Model 3032)	£ 795
CBM Dual Drive Floppy Disk System (Model 3040)	£ 795
CBM High Speed Printer (Model 2023)	£ 550
Total	<u>£2140</u>

i. The Micro Computer

The CBM 32K micro computer has a built-in monochrome television monitor and the operation of the screen keyboard and additional peripherals are controlled by an MCS 6502 micro processor.

Specifications for this model are given in Appendix 5.

The rate of development of desk-top computers is comparable to the development of calculators in the early 1970s. The particular computer used in this study has been upgraded twice in two years and the name 'PET' is now being dropped by the manufacturers.

ii. The Dual Drive Floppy Disk System

The CBM system shown in Fig.6.1 consists of read/write control, drive motor electronics, two drive mechanisms, two read/write heads, track positioning mechanisms and removable diskettes. It is an "intelligent" peripheral requiring no space in the computer's memory. The Disk System is controlled directly with BASIC commands given from the keyboard, from BASIC within the programmes and with special disk commands. The BASIC commands used to communicate and transfer data to and from the disk system are OPEN, CLOSE, SAVE, VERIFY, LOAD and PRINT. The syntax of these commands and the model specification are given in Appendix 6.

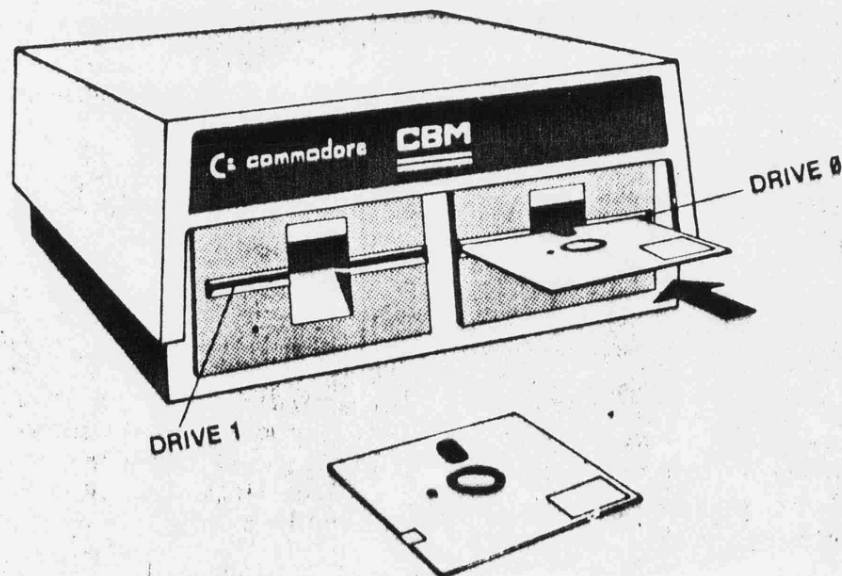


Figure 6.1

The 5¼" diskettes used are a standard flexible disk for soft sector format. The diskettes must be handled and stored with care. Exposure to magnetic fields can distort the data on disk as can abrasions or exposure to heat or sunlight. The DISK OPERATING SYSTEM (DOS) is responsible for managing all information between the disk controller and the IEE-488 bus.

The 3040 diskette initial command set consists of the following commands.

<u>Commands</u>	<u>Abbreviations</u>	<u>General Syntax</u>
BLOCK-READ	B-R	"B-R:ch,dr,t,s"
BLOCK-WRITE	B-W	"B-W:ch,dr,t,s"
BLOCK-EXECUTIVE	B-E	"B-E:ch,dr,t,s"
BUFFER-POINTER	B-P	"B-P:ch,p"
BLOCK-ALLOCATE	B-A	"B-A:dr,t,s"
BLOCK-FREE	B-F	"B-F:dr,t,s"
memory-write	M-W	"M-W"adl/adh/nc/data
memory-execute	M-E	"M-E"adl/adh
USER	U	"U1/:parms/"

Where: ch is the channel number in DOS: identical to the secondary address in the associated OPEN statement

dr is the drive number: 0 or 1

t is the track number: 1 through 35

s is the sector number: 0 through 20. For each track number, the sector range is:

<u>Track number</u>	<u>Block or Sector Range</u>	<u>Total</u>
1 to 17	0 to 20	21
18 to 24	0 to 19	20
25 to 30	0 to 17	18
31 to 35	0 to 16	17

p is the pointer position in the buffer

adl is the low byte of the address\*

adh is the high byte of the address\*

nc is the number of characters: 1 through 34\*

data is the number of bytes of data: 34 maximum

l is the index to the User Table

parms (optional) is the parameters associated with the U command.

\* Since these values exist in the 3040 as single bytes, the values with CHR\$(n) must be requested where n is the decimal value of the byte.

### iii. High Speed Printer

The CBM Printer (Fig.6.2) is designed to operate through software control and prints alphabetic, numeric and graphic characters. It prints 80 line columns at 60 lines per minute and has a burst speed of 150 characters per second.

The printer contains a micro processor system that resets and executes a diagnostic initialization sequence when power is applied. In addition it contains a random access memory (RAM) for the storage of formatting data. The printer is an "intelligent" peripheral and therefore does not use the computer's memory. (Appendix 7 ).

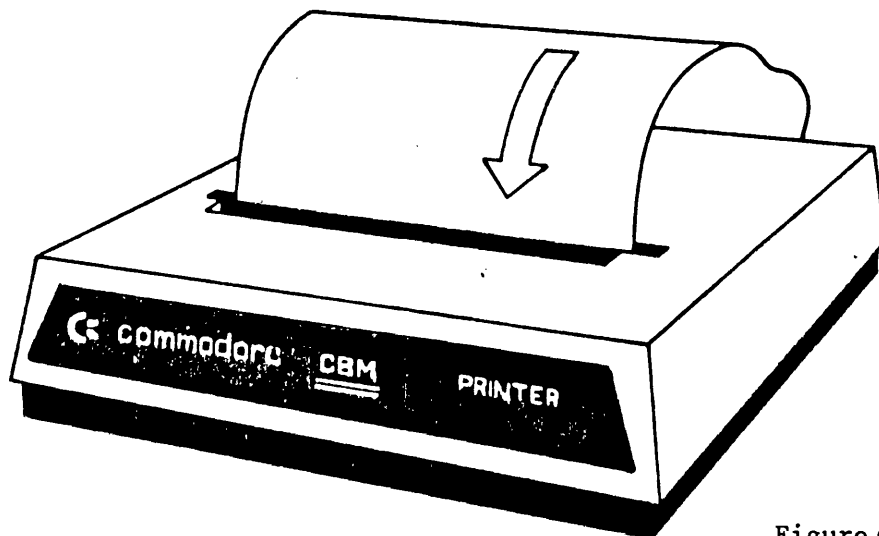


Figure 6.2

### Criteria used for Program Design

The models suggested in Chapter 5 are based on complex mathematical algorithms and their implementation requires the design of a comparatively large analysis package. The design of suitable computer programs was dependent to a large extent, on a number of criteria relating to the computer system, in particular:

- a. Ease of program development
- b. Program capability
- c. Ease of data entry
- d. Data storage facilities
- e. Speed of execution
- f. Suitability of output medium

It was considered that these could be satisfied using the system described.

a. Program Development

The language used to communicate with the CBM micro computer is BASIC. BASIC is a remarkably easy computer language to learn and use.

It is an interpretive language which means that, once a small section of program has been written, it can be tested without the need to compile it into the machine's own language, thereby making it easy to identify "bugs". BASIC's system of line numbering allows the machine to distinguish between commands which are preceded by a line number indicating that they form part of a program and commands not preceded by a line number indicating that they are to be executed in order of ascending line number. Therefore, it is possible to modify a program by adding extra lines with the appropriate line numbers. Groups of lines may be instantly recalled to the screen and modifications made by inserting, deleting or over writing as appropriate. These factors taken together, make program development as easy as possible while leaving a considerable degree of flexibility. Therefore, it satisfies criteria (a), ease of program development.

b. Program Capability

This is measured later in Section 6.5 using the 74 activity test model.

c. Data Entry

Data preparation of the kind required in these models for batch processing has traditionally been very time consuming and difficult to check and it is here that the visual display (VDU) is particularly useful. The visual impact of being able to see the information on the screen, together with the facility to correct entries makes data generation very quick and minimises errors.

d. Data Storage

It has been assumed in Chapter 5 that at least 90% of the activities have piecewise linear time cost curves with no more than three pieces and that the remaining 10% have time cost curves which can be defined by a schedule of costs for a maximum of 50 consecutive durations. So, for each activity there is a maximum of 10 numbers to record precedents 8 numbers to record a 3 piece linear time cost curve, one number to record average cost, and the equivalent of 20 real numbers is allowed for recording this basic data for each activity. In addition, provision is made to record up to 50 pieces of cost information for 10% of the activities. If N is the number of activities the amount of data can be estimated as:

$$(20 + 0.1 \times 50) \times N = 25N \text{ real numbers}$$

The programs described in Section 6.4 are designed to run on a micro computer with  $\leq 32K$  memory space. Assuming 7 bytes for each real number, and 10,000 bytes for the program, the maximum number of activities which can be held at once in memory is

$$N = \frac{(32,000 - 10,000)}{25 \times 7} = \frac{22,000}{175} = 125$$

It is advisable to leave space in the program for additional data generated by the program itself, which would, in fact, be needed if it were necessary to refine or amend the algorithm. It can be seen from Section 6.4 that this requirement for data storage is satisfied.

e. Speed of Execution

BASIC is slow by most computing standards. All BASIC calculations are performed in floating point mode and numbers stored in integer form have to be converted to and from floating point each time they are used. BASIC programs have to be interpreted first then executed.

An alternative is to use machine language programs which execute much faster than BASIC programs. In CBM there are two ways to create a machine language program in memory and execute it. The first is by BASIC, using the commands PEEK and POKE which give equivalent machine language operation relative to controlling input/output instructions or influencing or sampling individual memory locations. The second method is to program by a monitor. This latter approach was not considered as a monitor micro processor was not available.

The possibility of using machine language was considered in the early stages of the research. However, speed of execution is relative and was not considered to be a high priority criterion at this stage of development. Therefore, bearing in mind the ease with which BASIC can be written and the fact that the protection of the ROM fail safe coding is lost when machine language is used it was decided that BASIC was appropriate. A further important factor relating to implementation is the ease with which minor adjustments can be made to aspects of the program by personnel with a rudimentary knowledge of BASIC.

Another alternative considered was the use of PASCAL which is a language similar to BASIC. This language is reasonably easy to learn and is described in the form of a User Manual and Report by Jensen and Wirth.<sup>67</sup>

Commodore have produced a disk based compiler for use on their computers. This compiler transfers a program written in PASCAL into machine code which can be stored on disk or tape and loaded directly. Although faster in execution than BASIC the need for a compiler and the greater difficulties associated with inputting data and making minor adjustments to the program ruled out its use at this stage.

There is, of course, no reason why the programs could not be converted to a machine language at a later stage if considered appropriate.

It should be noted that although the programs are written in BASIC, it is that form of BASIC which is peculiar to the Commodore PET. In order to convert the programs to run on another machine, it would be necessary to make certain amendments. This applies principally to PET commands of the form: OPEN, CLOSE, INPUT, PRINT, which open and close channels of communication between the computer and the screen, the printer and the disks and read and write on them. Commands of this type would have to be changed to their equivalent for use with alternative computer models.

#### f. Output Data

Output can be displayed on the screen and/or sent to the printer. This feature is discussed and measured later in greater detail in that the format required varies with the needs of the recipient.

### 6.4 Computing Software System

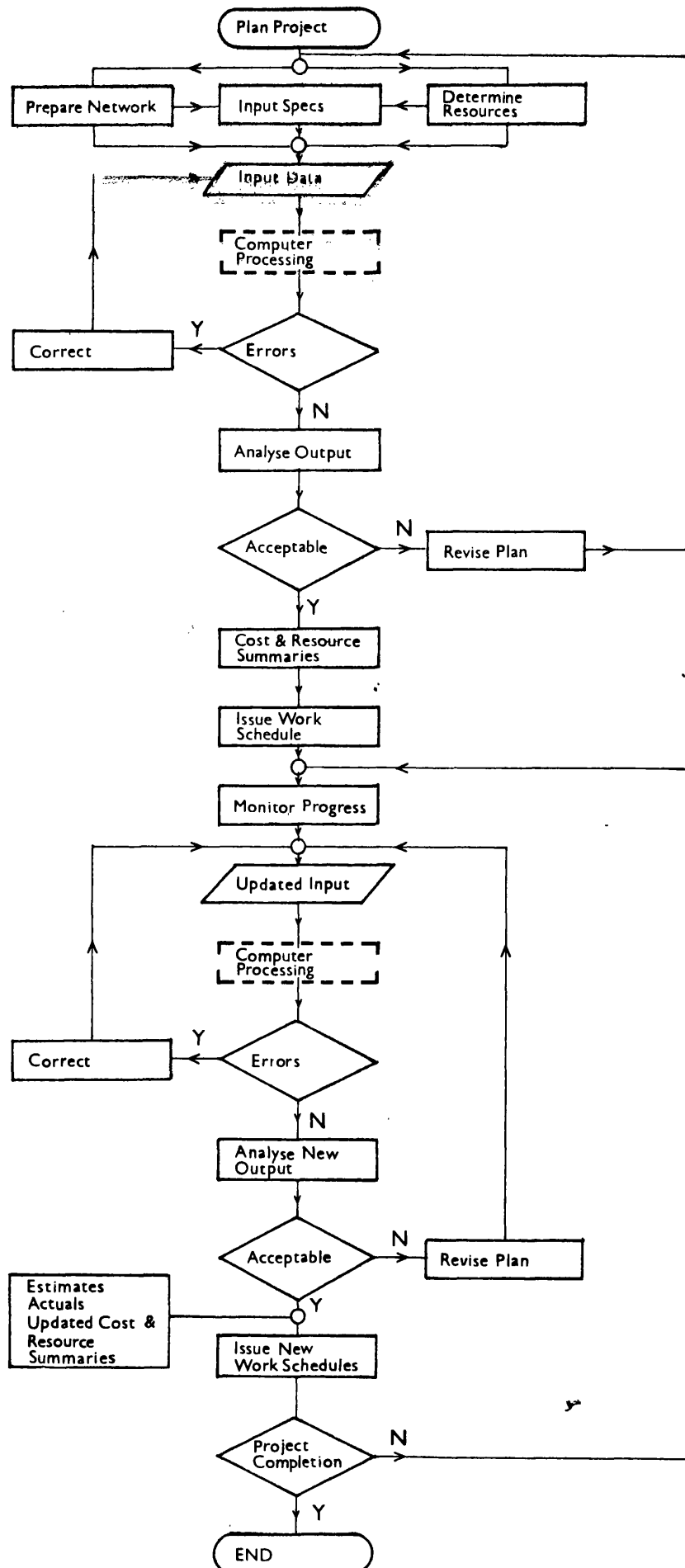
This section looks at the computer software designed specifically to implement the heuristic solution postulated in Section 5.5, Chapter 5. In addition, further software was designed to enable comparative tests to be undertaken between the heuristic and the integer linear programming models suggested in Sections, 5.2, 5.3, and 5.4, Chapter 5.

#### Software Development

The following sequence of activities was adhered to in developing the software for this research: -

- i. Specification of the required software
- ii. Software design
- iii. Coding and de-bugging the programs
- iv. Validation testing

The above sequence only defines the framework within which the program development is carried out and there is always an overlap between each stage and the activities.





which proceed and follow it. As part of the initial development of appropriate programs, the following factors had to be identified:

- i. The objectives of the program and the data manipulations which must be carried out.
- ii. The relationship, if any, between this program module and further modules.
- iii. The files or data base to be used in conjunction with the program and the data files affected by the manipulations carried out in the program.
- iv. The computer configurations to be used for the development and routine running of the program. This factor was influenced by the size of the main memory available for use with the programs and resulted in minor modifications to the original objectives.
- v. The peripherals to be used to input the required data to the system.
- vi. The contents and format of the input data.
- vii. The contents and format of the output data.
- viii. The peripherals to be used for preparing output reports.

These factors are not discussed at this point as they have been referred to earlier or are considered further as this section is developed.

Figure 6.3 sets out in flow chart form, the overall process relating to the planning, control and completion of a construction project. This places the requirements in terms of software into perspective, highlighting the requirements of the manager in terms of his role as a decision maker.

#### Data Files

The data is held on disk in four separate files, viz. NUMBER, A\$MATRIX, AMATRIX, and PMATRIX.

NUMBER records the number of activities in the project: A\$MATRIX records the descriptions of each activity: AMATRIX records a 100 x 20 matrix to hold 20 real number pieces of information for each activity that constitutes the project. This includes the crash duration (Cd), minimum cost durations (Mcd) and intermediate low (ILd) and intermediate high durations (IHd) with their respective precedents, direct costs and indirect costs per time unit; AMATRIX records a 10 x 50 matrix of detailed costings for consecutive durations for up to 10 specified activities. These costings extend at unit time increments from crash duration (Cd) to minimum cost duration (Mcd). If an activity is recorded in PMATRIX then it is assumed that detailed costing is available for that activity.

The challenge in the programming task was to provide a general purpose model that would accept continuous changes with a high degree of flexibility.

Because of the nature of the construction process changes in plan are inevitable and it is important to recognise and provide for change.

The design of the programs therefore accepts:

- i. That planning is imperfect and new perspectives will continually emerge.
- ii. Events in the more immediate future can be forecast with much greater accuracy.

There are three major operations to be accounted for:

- i. Inputting the data.
- ii. Amending the data.
- iii. Analysing the data with respect to sequence, interrelationships, etc.

Therefore, three main programs were written in BASIC to run in the 32K micro computer. These were called INCRIT-T/C, AMCRIT-T/C, and ANCRIT-T/C, respectively. (Appendix, 8, 9, 10).

Having established a specification for the overall system requirements, an individual specification was prepared for each program and a series of flow charts drawn up and progressively amended until the logic of each program and the overall system were satisfied.

A brief description and simplified flow chart follows for each of the three main programs. (Detailed flow charts are available for each program.)

#### INCRIT-T/C

This program writes to disk the data required to run program ANCRIT-T/C.

It inputs the number of activities (data file - NUMBER), the description of each activity (df - A\$MATRIX). For each activity description Mcd, Mc, Cd and Cc are input with optional provision for ILd, IHd, ILdc, IHdc and the number of precedents (df - AMATRIX). Detailed costing is input using data file PMATRIX. The program is designed to be largely self-explanatory, requesting data as set out on the program input sheets (Appendix 12). The input is requested in the following order:

- i. Number of activities ( maximum of 100)
- ii. Contract description (alpha-numeric)
- iii. Activity description (alpha-numeric) - for each activity
- iv. Numeric data reference number
- v. For each activity:
  - a. Minimum cost duration (Mcd)
  - b. Minimum Cost (Mc)
  - c. Crash Duration (Cd)
  - d. Crash Cost (Cc)

v. continued

e. Optional data:

Intermediate low duration (ILd)

Intermediate low duration cost (ILdc)

Intermediate high duration (IHD)

Intermediate high duration cost (IHdc)

f. Number of precedents (0 - 9)

(Note: only the first activity has no precedent;  
only the last activity is never a precedent)

g. Precedents in ascending order

(The program is designed to ensure that this sequence is adhered to)

vi. Indirect costs per time unit

vii. Detailed costing reference number

viii. Activity number for which detailed costing is required ( 0 to end)

iv. Cost for each duration (durations are given in unit increments between  
crash and minimum cost durations)

nb. Up to 10 activities can have detailed costing, with up to 49 intermediate  
points each - if the operator attempts to exceed these limits the detailed  
costing data is not written to disk.

If an activity number for detailed costing is inadvertently repeated, the  
existing data for that activity is listed, giving the operator the opportunity  
to alter any data items.

The program provides the opportunity to retype a set of data, after the  
program has listed the data just typed. If the data is input incorrectly,  
is not within stated limits, or does not satisfy certain basic conditions,  
the program will identify these types of error. The following constant  
applies to all activities:

$Cd \leq ILd \leq IHD \leq Mcd$

$Mc \leq IHdc \leq ILdc \leq Cc$

A simplified flow chart is given in Figure 6.4 and Schedule 6.1 lists the  
routines for this program.

# INCRIT FLOW CHART

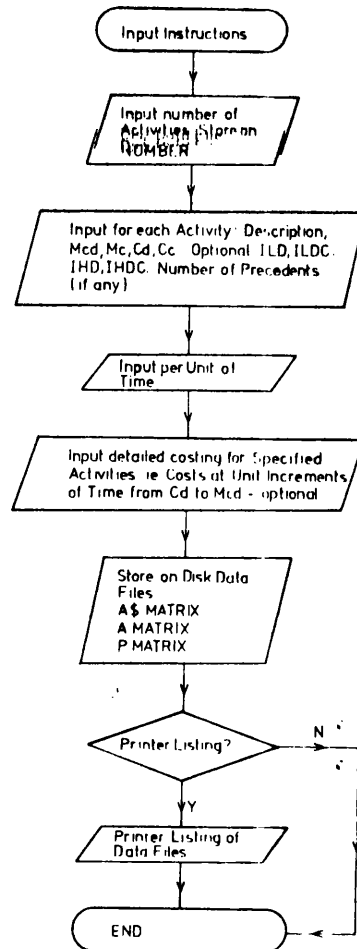


Figure 6.4

## SCHEDULE 6.1 - INCRIT-T/C

### Main Program: Input explanation

Input number of activities  
 Input indirect costs per time unit  
 Printer listing

### Sub-routines

- |    |  |
|----|--|
| 2a | Any changes, Y or N request  |
| 2  | Y or N request   |
| 3  | Write 21 to disk - number (number of activities)                     |
| 4  | Input data for each activity (activity description and numeric data) |
| 5  | Write A(I,J) to disk - AMATRIX (numeric data)                        |
| 6  | Write A\$(I) to disk - A\$MATRIX (activity description)              |

```

7      Read NUMBER, printer listing
8      Read A$MATRIX, printer listing
9      Read AMATRIX, printer listing
10     Write PJ (I,J) to disk - PMATRIX (detailed costing)
11     Read PMATRIX
12     Detailed costing input data
13     Screen listing detailed costing
14     PMATRIX, printer listing
15     Deriving cost slope
16     Check for disk error
17     Check on disk status when reading data file

```

#### AMCRIT-T/C

This program allows the data to be amended in respect of activity description (N), numeric data (D), indirect costs (H) and detailed costing (C), for all activities that constitute the project.

By opening a new data file, eg. NUMBER 2, A\$MATRIX 2, AMATRIX 2, PMATRIX 2, the original data can be retained.

To change NUMERIC DATA (D) for example, the following schedule (Figure 6.5) of existing data is displayed on the screen for the activity under review - say, Activity 59 for the model network shown in Figure 6.12.

#### EXISTING DATA FOR ACTIVITY 59

1 - 21	11 - 0
2 - 2	12 - 0
3 - 19	13 - 2
4 - 20	14 - 190
5 - 99.9	15 - 2
6 - 0	16 - 190
7 - 0	17 - 190
8 - 0	18 - 2
9 - 0	19 - 190
10 - 0	20 - 2

Figure 6.5

#### NEW DATA FOR ACTIVITY 59

1 - 21	11 - 0
2 - 11	12 - 0
3 - 19	13 - 2
4 - 20	14 - 8000
5 - 99.9	15 - 2
6 - 0	16 - 190
7 - 7	17 - 5705
8 - 0	18 - 5
9 - 0	19 - 9350
10 - 0	20 - 0

Figure 6.6

When the number/s of the data to be altered is typed in, the amended schedule is displayed on the screen/print out, (Figure 6.6). Indirect and detailed costings can be amended in the same way. A printer listing of the data files can be obtained if required. A simplified flow chart is given in Figure 6.7, Schedule 6.2 lists the program's subroutines.

# AMCRIT FLOW CHART

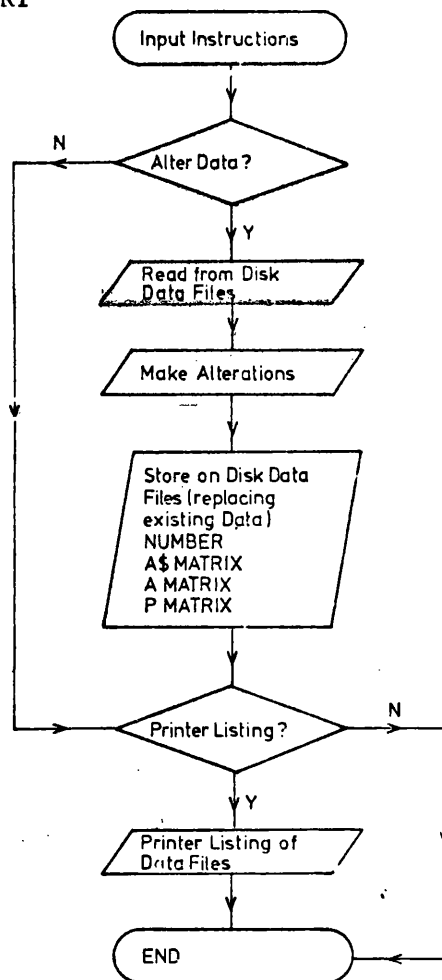


Figure 6.7

## SCHEDULE 6.2 - AMCRIT-T/C

Main Program: Input explanation  
 Type of alternation required  
 Printer listing

### Sub-routines

- 1 Read NUMBER
- 2 Y or N request
- 3 Write PJ (I,J) to disk - PMATRIX (detailed costing)
- 4 Read AMATRIX
- 5 Read A\$MATRIX
- 6 Read PMATRIX
- 7 Check existence of detailed costing
- 8 Alter numeric data
- 9 Alter activity description
- 10 Alter detailed costing
- 11 Write A (I,J) to disk - AMATRIX (numeric data)
- 12 Write A\$ (I) to disk - A\$MATRIX (activity description)
- 13 Press any key to continue
- 14 Check typed input
- 14A Any changes

- 15 Wait for end of run
- 16 Screen listing numeric data
- 17 Screen listing detailed costing
- 18 Alter indirect costs per time unit
- 19 NUMBER, printer listing
- 20 ~~AMATRIX~~, printer listing
- 21 ~~AMATRIX~~, printer listing
- 22 PMATRIX, printer listing
- 23 Write 21 to disk - NUMBER (number of activities)
- 24 Deriving cost slope
- 25 Check for disk error
- 26 Check on disk status when reading data file.

#### ANCRIT-T/C

This program reads the data from the data files and carries out a forward and backward sweep through the matrix defining multiplicity, time, cost and critical path, speeding up or relaxing activities, as appropriate. The program first calculates the total duration and cost for the project assuming each activity states minimum cost and project duration. The project duration is then progressively reduced by speeding up the critical activities with the lowest time cost slope. The process is repeated if a further reduction is possible. When no further reduction is possible, a summary output is given with a printer listing of the data files, if required. Since the data for this program is already held on disk, the only input required from the operator is for the following options:

- i. Type S, P or B  
For output on the screen, printer or both.
- ii. Type Y or N  
(For yes or no), for detailed information for each project duration.
- iii. Type Y or N  
(For yes or no) for a printer listing of the data held on disk.

A simplified flow chart is given in Figure 6.8 and Schedule 6.3 lists the program's sub-routines.

# ANCRIT FLOW CHART

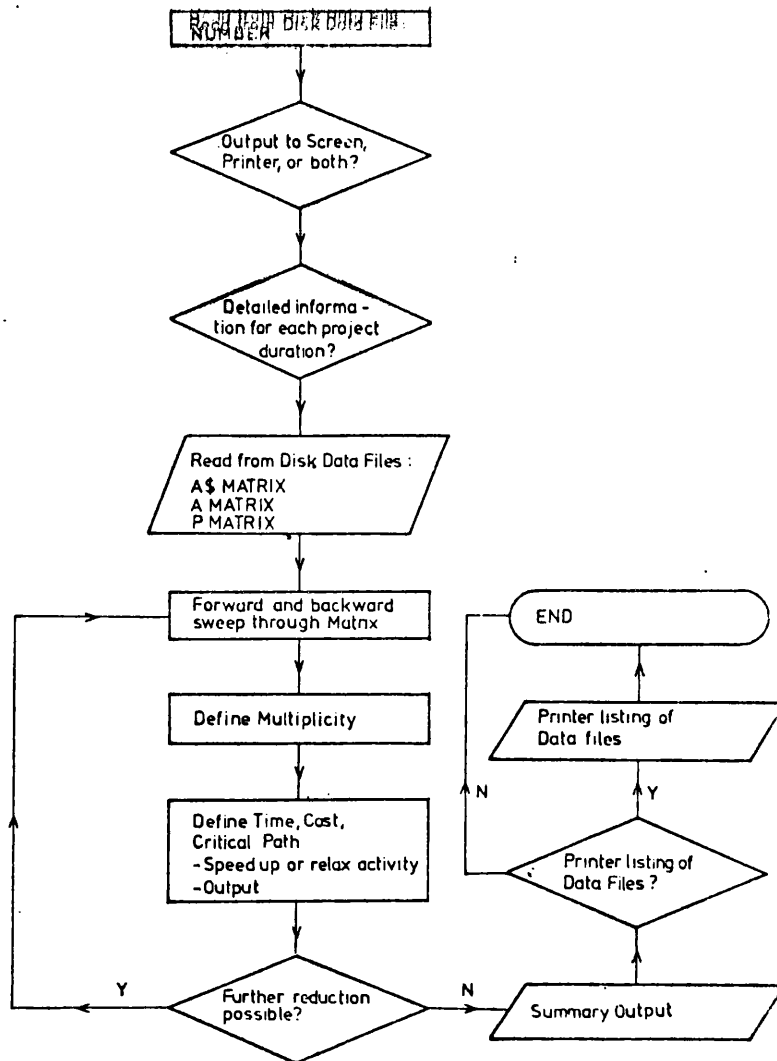


Figure 6.8

## SCHEDULE 6.3 - ANCRIT-T/C

Main Program Options: Output on screen, printer or both, detailed information for each project duration.

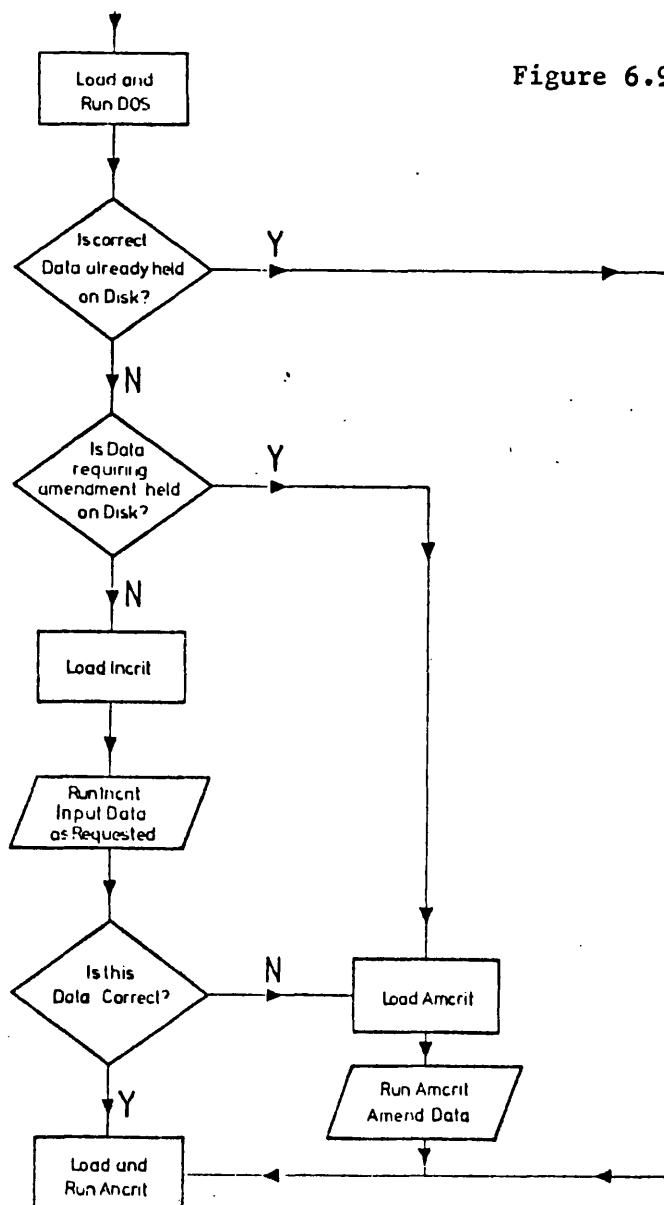
### Sub-routines

- 1 Forward and backward sweep through matrix
- 2 Multiplicity
- 3 Multiplicity
- 4 Time, cost, critical path
- 5 Output
- 6 Screen output - activity data, critical path
- 7 Screen output - project duration, costs
- 8 Printer output - activity duration, critical path
- 9 Printer output - project duration, costs
- 10 Printer output - T\$ across page
- 11 Critical activity to speed up
- 12 Speed up activity
- 13 Printer output - speed up, cost increase
- 14 Printer output - relax, cost saving
- 15 No reduction possible



16 Printer output - durations, costs  
 17 Screen output - durations, costs  
 18 Press any key to continue  
 19 Data listing on printer  
 20 Read NUMBER  
 21 Type Y or N  
 22 Read AMATRIX  
 23 Read A\$MATRIX  
 24 Read PMATRIX  
 25 Printer listing - number of activities  
 26 Printer listing - activity description  
 27 Printer listing - numeric data  
 28 Printer listing - detailed costing  
 29 Check for disk error  
 30 Check on disk status when reading data file  
 31 Set money values to 2 decimal places

Figure 6.9



Input sheets for AMCRIT-T/C and INCRIT-T/C/AMCRIT-T/C are shown in Appendix 11 and 12 respectively.

A flow chart illustrating the overall computer system is shown in Figure 6.9. DOS is a standard support program designed by Commodore and available on disk allowing easy entry into the system.

#### De-bugging the Programs

It was, of course, necessary to test and verify these programs to ensure that they met the requirements specified and satisfied the initial design.

There are two main types of errors associated with the software development process:

1. Coding errors
2. Design errors.

Coding errors take the form of wrongly composed statements which are not in accordance with the procedure specified for the source language. Coding errors are also caused by omissions such as colon, semi-colon, comma, etc. The majority of these are identified by the computer during the process of development. Design errors relate to the logic of the program and are more difficult to eradicate than coding errors. The main sources of design errors were found to be ambiguity and an inadequate definition of the relationship between different sections of the program. It was considered desirable to eliminate this type of error during the design phase instead of carrying them over to the testing phase, and this approach was in fact the one successfully adopted. Had the latter approach been adopted it is possible that significant design errors might not emerge until a particular combination of data was used and might not then become apparent. The evaluation and testing of the models using these programs are discussed in the following section.

#### 6.5 Evaluating and Testing the Models

The major stages of the program development process are illustrated in the form of a flow chart (Figure 6.10).

The testing and evaluation of models such as the ones suggested in this research present a number of difficult problems. Kuehn and Hamburger<sup>64</sup> emphasise the fact that the evaluation of heuristic models is usually based on their usefulness rather than on their ability to attain an optimum solution.

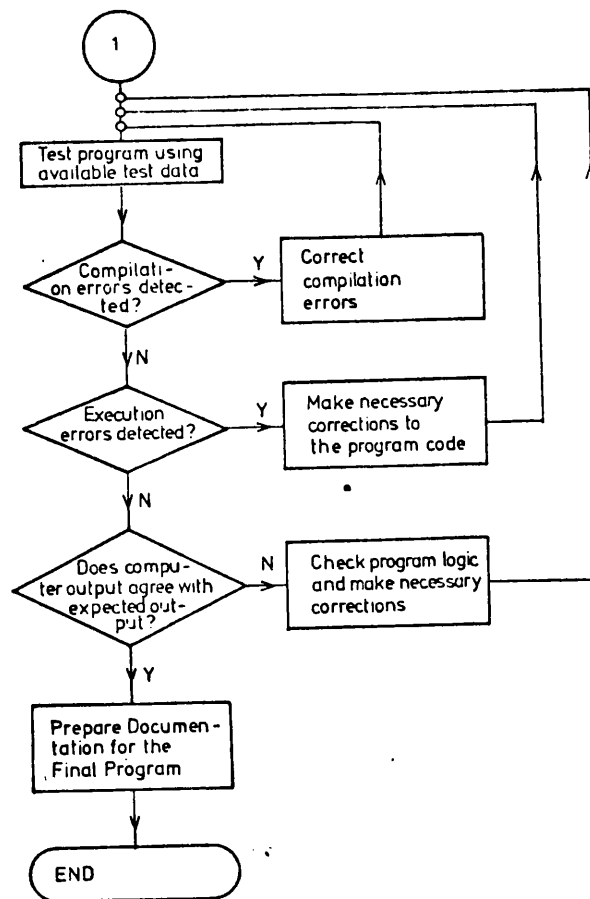


Figure 6.10

The quality of the solution is, however, only one of several criteria to be considered. Such features as computational efficiency and simplicity and the ability to adequately reflect real world complexities and constraints are often of considerable significance.

Criteria such as those suggested above are difficult to evaluate because adequate standards of comparison are rarely available. The answer to "What constitutes a good solution?" depends to a large extent on each organisation's and/or individual project's situational requirements, i.e. in one instance, meeting the target date for a project may be very important, in another, minimal cost or holding within other resource constraints may have a greater significance. (As it happens, the models suggested have, in fact, the capacity to satisfy either of these constraints.)

Evaluation of computational efficiency is also difficult to judge against absolute standards other than, say, computer time in hours, as compared with capital outlay in terms of the cost of buying equipment or hiring remote computer time.

Several possible methods of testing the models were considered:

- i. Comparative tests using small models capable of solution by manual methods.
- ii. Comparative tests between the heuristic model and other manual or computerised models used in practice.
- iii. Setting up a series of long term test situations on construction sites in planning departments, etc. to assess the effectiveness of the iterative model in practice.
- iv. Test the heuristic model using networks used in practice, for projects completed or ongoing.
- v. From experience and discussions with the sample companies, produce a simulation model into which a wide range of more complex time cost relationships could be incorporated.
- vi. Test the computational accuracy of the heuristic model using test data, against the more precise integer linear programming models using simulated data.

The approach suggested in (1) above was introduced early in the research as part of the process of developing a time cost theory (see Chapter 4). When the initial integer linear programming solution was developed this was again tested manually using small models, as was the modified integer linear programming solution and finally the heuristic approach. Attempts were made to computerise the heuristic approach at an early stage with little or no success. When a computerised solution was finally produced this was tested on a small 7 activity project. This solution was compared with a manual approach using integer linear programming and later with a computerised integer linear programming model on MULTICS. This is discussed in greater detail later in this section.

Approach Number 2 commends itself until it is appreciated that there was no comparable system operating in the sample companies or in any other construction company, judging from replies to the Questionnaire, (Chapter 1). This method of testing could not therefore be implemented.

Approach Number 3 on the face of it provides the ultimate test in terms of the effective application of the system, in practice. There were, however, a number of reasons why this was again, not feasible:

- i. To be realistic in practical terms, the test would need to be carried out over a period of 18 - 24 months. This was not possible within the timetable of this research programme, i.e. the development of the

mathematical models and the production of the computer programs were not completed until April 1981.

- ii. Two or possibly more, micro computing systems would need to be purchased and would be required for exclusive use in this research. This was not economically viable in that funds were not available to purchase the hardware required.

Although one of the sample companies had actually purchased a micro computer (16K with cassette peripheral only), this was being used exclusively for payroll and inventory and was fully committed on these functions. None of the other sample companies had micro computing facilities and were not in a position to purchase hardware purely to test the effectiveness of the models developed in this research programme.

This type of field test was, therefore, out of the question at this stage. It is the intention, however, to pursue this type of testing procedure and an application has been made for external funding. (See further research, Chapter 8.)

Although accepting the advantages of practical field tests, in that they are often considered to provide the "acid test", they suffer, when limited to one or two projects, from the inherent disadvantage of lack of breadth and possibly, complexity, both of which are essential features in testing the ability of the model to cope with a wide range of time cost relationships. Accordingly, a large number of differing types of projects need to be studied to achieve the required level of confidence in the test results.

The significance of this problem was further highlighted when approach Number 4 was considered. There were very few project networks available and those that were examined suffered from the defects mentioned above for ongoing projects. In addition the time parameter only was considered and it was impossible to obtain related cost data in sufficient detail to produce "actual" time cost curves. There was, therefore, little to be gained from this approach.

It was decided therefore, that the most appropriate approach was to construct a model using data that would simulate a wide range of complex time cost relationships, i.e. Approach 5.

Approach 6 is somewhat different in nature in that the objective here is to compare the computational accuracy of the heuristic model, with the more mathematically precise solution obtainable, using integer linear programming. A comparative test is described on Pages 172-180. Due to the number of constraints and variables involved in the integer linear programming approach, it is only possible to carry out the test on a relatively small network.

#### Simulation Test Model 1 - The Heuristic Approach

The micro computer based system designed in order to implement the heuristic model developed in Chapter 5 is illustrated in Figure 6.11.

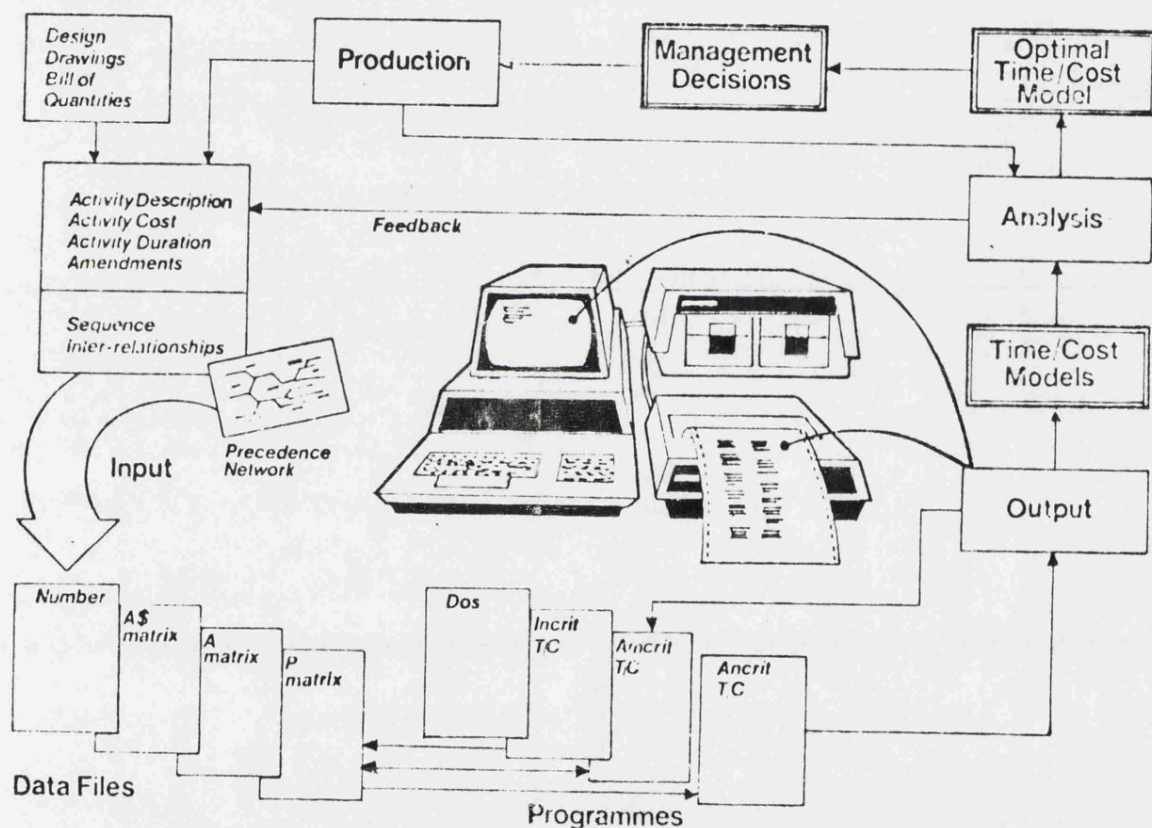


Figure 6.11

The objective in structuring the test model was to simulate "real world" activities at the same time introducing a variable range of complex activity and time cost relationships. The logic used is based on an actual project phase incorporating 74 activities, that, was originally planned using the "activity on the arrow" technique. The sequence and interrelationships between the individual activities has been rearranged to meet the research objectives and the network represented in the form of a precedence diagram (Figure 6.12) to satisfy the general preference for this method of presentation.

### Model Data

The activity durations used, although based on actual project information, have been modified substantially to suit the test objectives. All cost information is simulated.

The initial test data includes Minimum Cost Duration (Mcd), Crash Duration (Cd), Minimum Cost (Mc), and Crash Cost (Cc) information only. The first computer run analyses Mcd and Mc data (Figure 6.12) giving full input and output data on the VDU screen, the printer, or both, as required.

As the project is speeded up the critical path/s increases in complexity. The program identifies and examines each critical path, searching out those critical activities with the lowest cost slope. The direct and indirect costs associated with each incremental unit time reduction are then derived until crash duration is reached and critical activities are at crash cost. The multiple critical paths that emerge when the project as a whole is crashed, are shown in Figure 6.13. Variations in the critical path occurred as the cost slope and multiplicity of critical activities were examined by the program and individual activities were speeded up or relaxed.

It is interesting to note that the original critical path (Figure 6.12), is still present. Detailed input and output data can be observed on the VDU screen and/or the printer for each incremental unit time reduction, if required.

### SCHEDULE 6.4 - Computer Print Out

Project Duration	Project Costs		
	<u>Indirect</u>	<u>Direct</u>	<u>Total</u>
90	45000.00	63191.00	108191.00
89	44500.00	63203.50	107703.50
88	44000.00	63216.00	107216.00
87	43500.00	63240.00	106740.00
86	43000.00	63270.00	106270.00
85	42500.00	63320.00	105820.00
84	42000.00	63370.00	105370.00
83	41500.00	63420.00	104920.00
82	41000.00	63475.00	104475.00
81	40500.00	63575.00	104075.00
80	40000.00	63697.22	103697.22
79	39500.00	63819.44	103319.44
78	39000.00	63941.67	102941.67
77	38500.00	64063.89	102563.89
76	38000.00	64186.11	102186.11

Schedule 6.4 continued

<u>Project Duration</u>	<u>Indirect</u>	<u>Project Costs</u>	<u>Direct</u>	<u>Total</u>
75	37500.00		64308.33	101808.33
74	37000.00		64430.56	101430.56
73	36500.00		64552.78	101052.78
72	36000.00		64675.00	100675.00
71	35500.00		64865.00	100365.00
70	35000.00		65090.00	100090.00
69	34500.00		65315.00	99815.00
68	34000.00		65541.25	99541.25
67	33500.00		65767.50	99267.50
66	33000.00		65993.75	98993.75
65	32500.00		66220.00	98720.00
64*	32000.00		66660.00	98660.00
63	31500.00		67433.75	98933.75
62	31000.00		68487.50	99487.50
61	30500.00		68991.25	99491.25
60	30000.00		69585.00	99585.00
59	29500.00		71348.33	100848.33
58	29000.00		72261.67	101261.67
57	28500.00		73325.00	101825.00

As can be seen from Schedule 6.4, the project has been reduced from 90 time units to a crash duration of 57 time units. The direct cost has increased from £63,191 to £73,325 and the indirect costs have decreased from £45,000 to £28,500. The overall cost has decreased from £108,191 to £101,825. The project duration cannot be reduced beyond this point and the criteria for minimum project duration has been achieved. However, this is not the optimum project duration in terms of minimum cost. This relationship is, in fact, optimised at a project duration of 64 time units. It can be seen from Schedule 6.4 that the direct, indirect and overall costs at this point are £66,660, £32,000 and £98,660 respectively.

Variable data was then introduced to test the changes induced in the critical path/s for example:

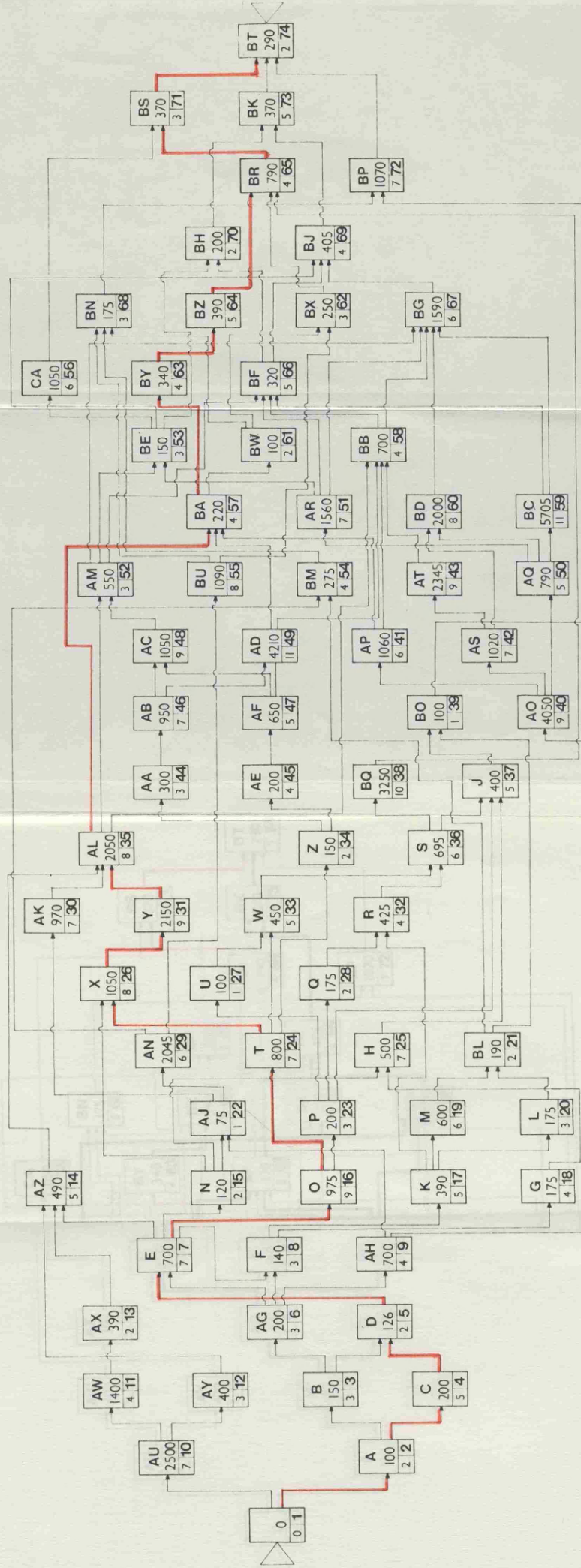
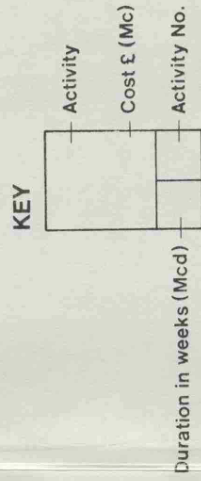
Assume that Activity 39, which so far has not appeared on the critical path, is delayed by 23 time units. The minimum cost critical path produced is shown in Figure 6.14. The project duration is now 90 time units. Activity 16 is speeded up first, reducing the project duration to 89 time units but with no change in the critical path. Next activity 39 is reduced and the resulting critical paths are shown in Figure 6.15. Activity 4 is now speeded up with the result that a new critical path is introduced (shown in green in Figure 6.16).



# PRECEDENCE CHART — 74 ACTIVITY PROJECT

All activities at Minimum Cost (Mc) & Minimum Cost Duration (Mcd)

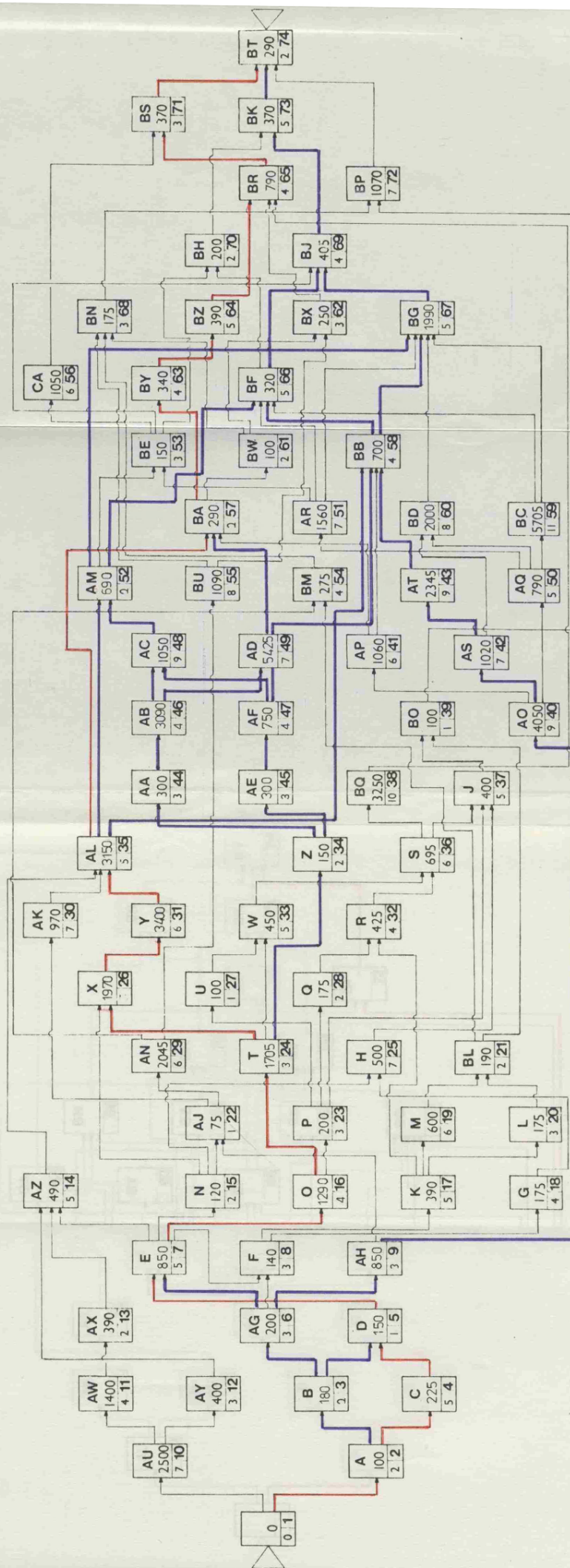
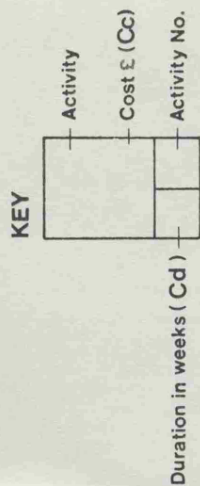
FIG 6.12



# PRECEDENCE CHART — 74 ACTIVITY PROJECT

All activities at Crash Cost (Cc) & Crash Duration (Cd)

FIG 6.13

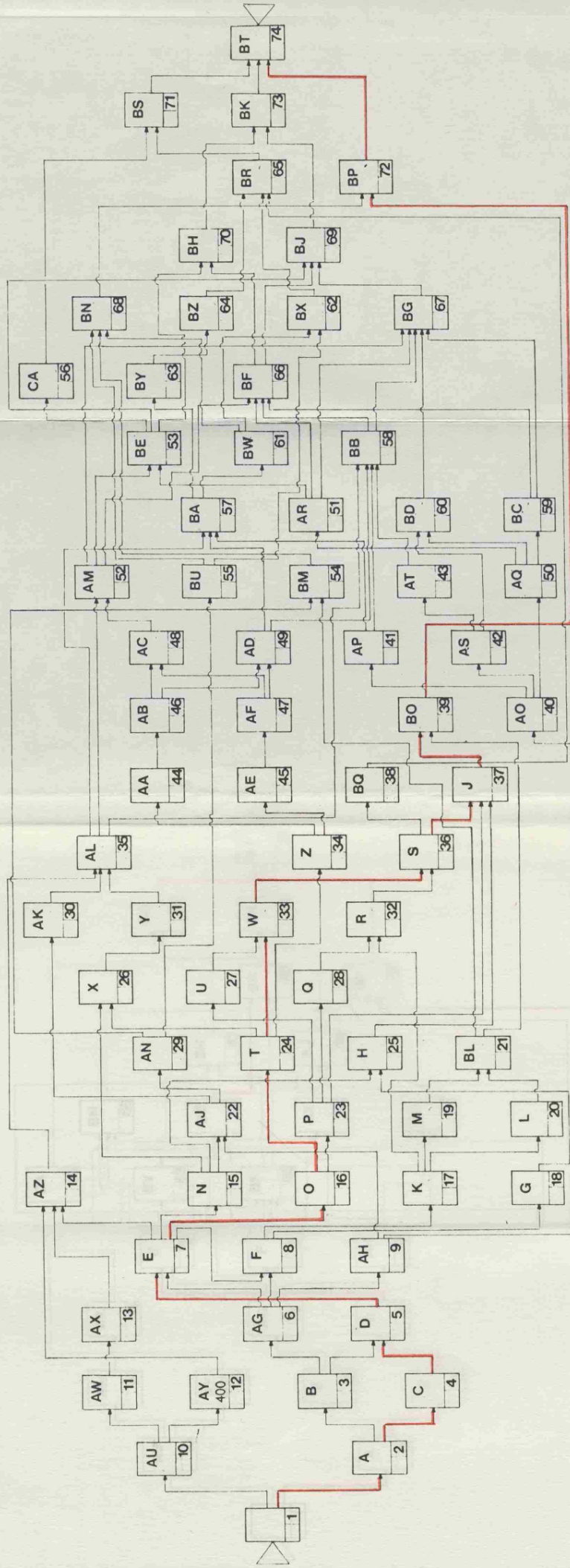
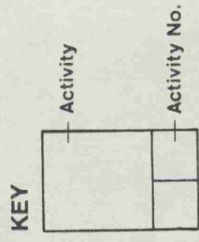




# PRECEDENCE CHART — 74 ACTIVITY PROJECT

With variable data inputs

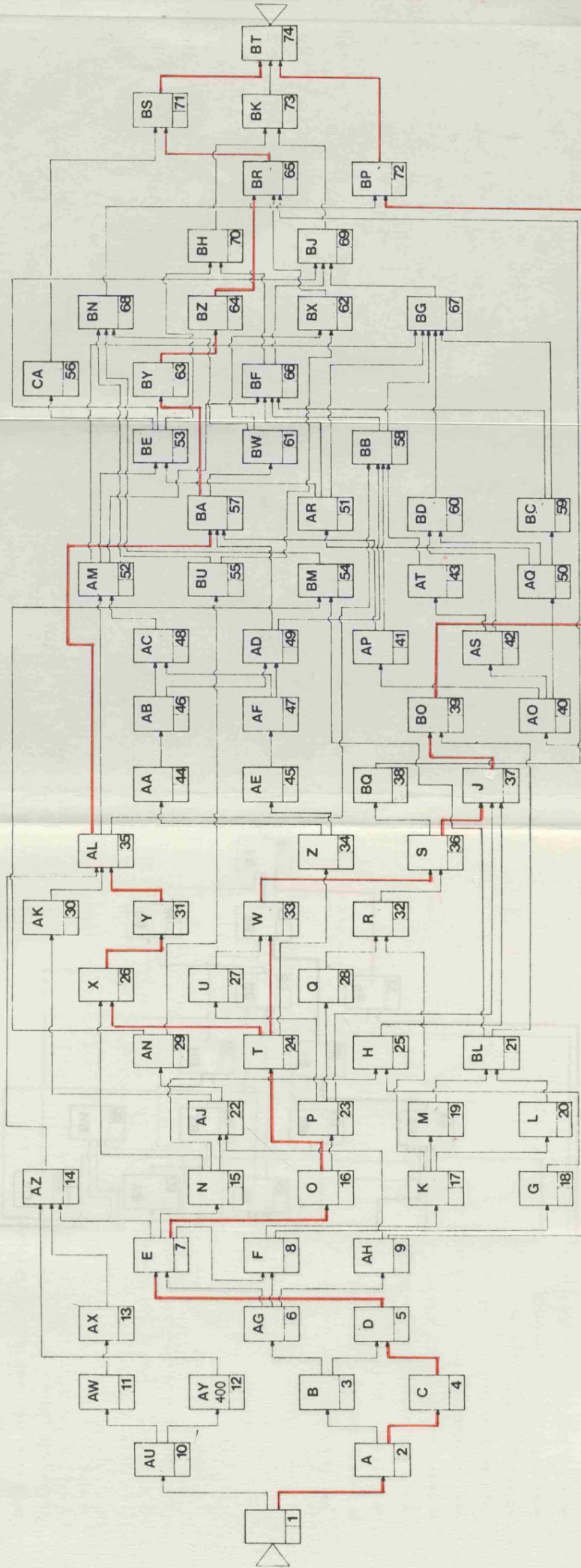
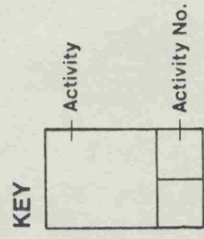
FIG 6.14



# PRECEDENCE CHART — 74 ACTIVITY PROJECT

With variable data inputs

FIG 6.15

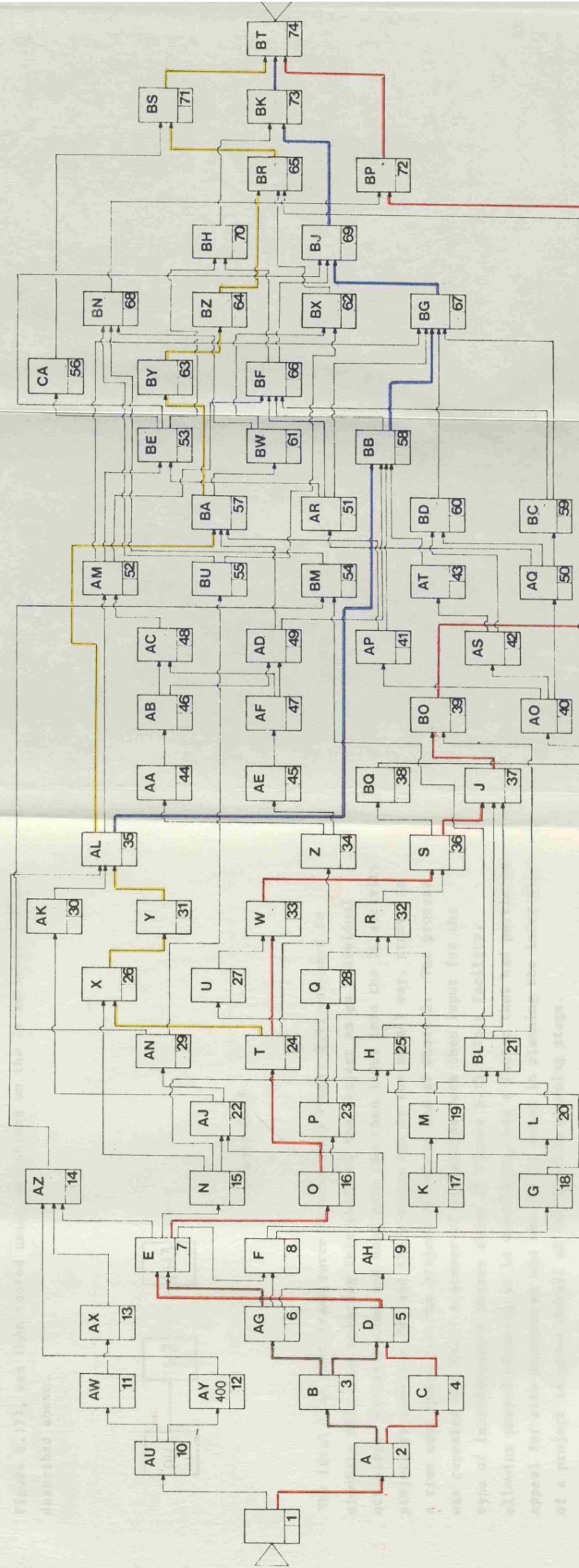
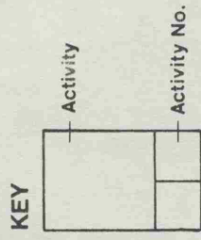




# PRECEDENCE CHART — 74 ACTIVITY PROJECT

With variable data inputs

FIG 6.16



At the next stage activities 57 and 39 are both speeded up resulting in a new branch to the critical path (shown in blue in Figure 6.16). The paths shown in green and yellow are illustrative of the way in which the critical paths elaborate as the project approaches crash duration. The shape and nature of the cost slopes were then further varied using a wide range of time cost input, and the effect on the project examined. As described above, the critical paths varied in number and complexity. It was noticeable that, in the main, once an activity became critical it remained so.

The suitability of the model for use in phased projects, (PH1, PH2, PH3 - Figure 6.17), was then tested using variations on the 74 activity project described above.

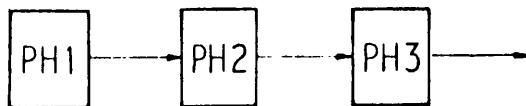


Figure 6.17

The total time cost crash curve derived from Figure 6.13 was used to simulate PH1, thus treating this phase of the project as an individual activity. Variable time and cost data was then input into the 74 activity project to simulate PH2 and the program run in the normal way, producing a time cost curve for the project up to the end of Phase 2. The process was repeated for PH3. A number of variations were then input for the type of interdependant phases shown in Figure 5.15. This facility, allowing phased planning to be undertaken, was a factor that had particular appeal for site management who saw little point in planning the later phase of a project in great detail at the initial planning stage.

During these tests the model proved capable of coping with an extremely wide range of alternative strategies, allowing the project to be sub-divided into a large number of phases. It should be noted that AMCRIT is designed in such a way as to allow new data to be added without destroying the existing data bases thus enabling the logic of alternative strategies to be re-examined at any stage.

It can be seen from the foregoing that a wide range of tests were used to establish the effectiveness of the heuristic model. Those described

have been selected as illustrative of the way in which the objectives of the research have been achieved. As intimated earlier the integer linear programming models could be expected to be more precise than the heuristic model in terms of computational accuracy. It was decided, therefore, to implement approach 6 whereby the two models could be used to check one another in this respect.

As shown earlier the integer linear programming models contain a large number of constraints and variables. They are, therefore, not applicable to other than very small project networks when used in conjunction with a micro computer. The comparative example (Figure 6.16) is therefore based on a 7 activity project which has the added advantage that it can also be checked manually.

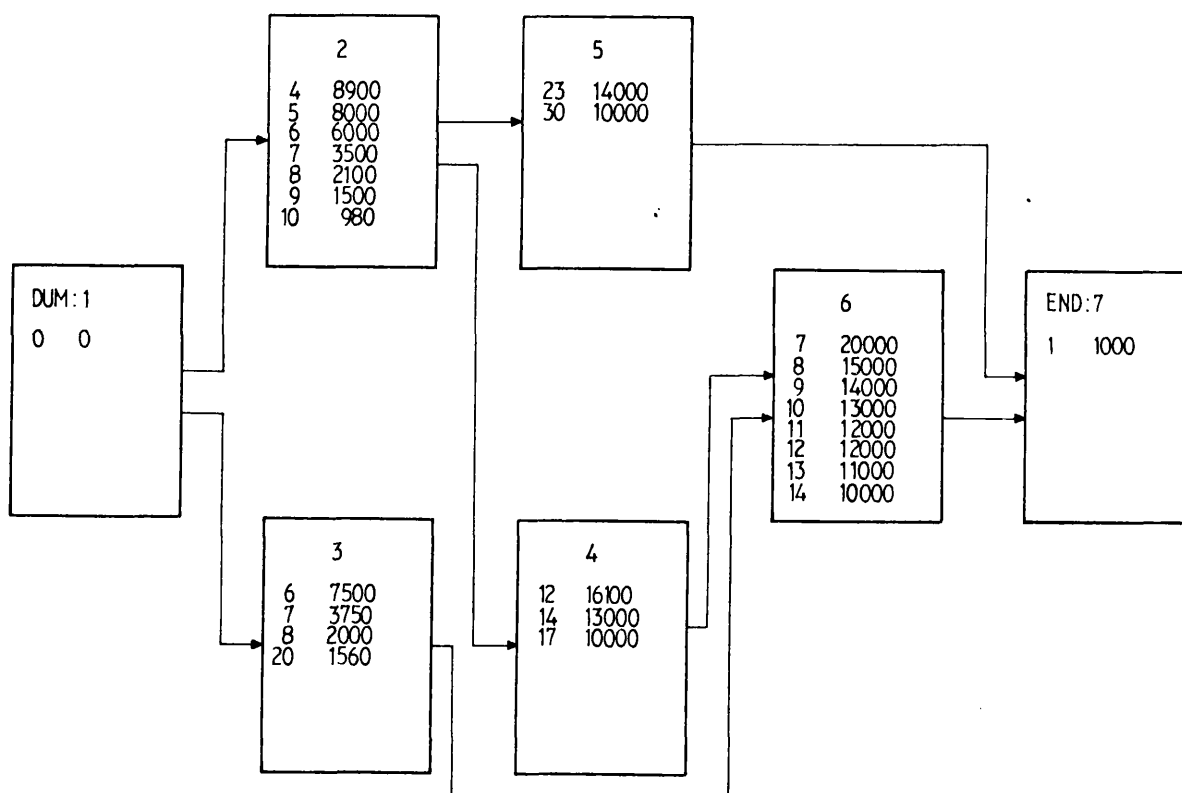


Figure 6.16

This comparative analysis is now described in detail.

i. Integer Linear Programming Formulation for a 7 Activity Project

The data for the project is input and recorded on disk via an interactive program on the 32K PET micro computer. The program input requires the number of activities, the description of the activity, the precedence relations with other activities, and the time cost data. A print out of the project data is shown below, (Schedule 6.4).

i. contd..

There are three files, one for activity descriptions, one for basic activity data including precedence and basic cost, and one for detailed costing. In the case of this project there were two detailed costings, one for Activity 2 and one for Activity 6. In general, detailed costing has to be declared when there are more than three linear pieces in the time cost curve. Activity 3, for example, represents the most complex cost relationship that is possible without using detailed costing.

#### SCHEDULE 6.4

DATA WRITTEN TO DISK FROM AMCRIT PROGRAM

NUMBER OF ACTIVITIES 7

CONTRACT DESCRIPTION

TRIAL

ACTIVITY NUMBER	ACTIVITY DESCRIPTION
1	DUM
2	A
3	B
4	C
5	D
6	E
7	END

NUMERIC DATA REFERENCE NUMBER 0

1 - 1	6 - 0	11 - 0	16 - 0
2 - 0	7 - 0	12 - 200	17 - 0
3 - 999	8 - 0	13 - 0	18 - 0
4 - 0	9 - 0	14 - 0	19 - 0
5 - 0	10 - 0	15 - 0	20 - 0
1 - 2	6 - 0	11 - 0	16 - 980
2 - 10	7 - 0	12 - 0	17 - 980
3 - 1	8 - 0	13 - 4	18 - 4
4 - 999	9 - 0	14 - 8900	19 - 8900
5 - 0	10 - 0	15 - 10	20 - 520
1 - 3	6 - 0	11 - 0	16 - 2000
2 - 20	7 - 0	12 - 0	17 - 1560
3 - 1	8 - 0	13 - 7	18 - 6
4 - 999	9 - 0	14 - 3750	19 - 7500
5 - 0	10 - 0	15 - 8	20 - 36.67
1 - 4	6 - 0	11 - 0	16 - 13000
2 - 17	7 - 0	12 - 0	17 - 10000
3 - 2	8 - 0	13 - 14	18 - 12
4 - 999	9 - 0	14 - 13000	19 - 16100
5 - 0	10 - 0	15 - 14	20 - 1000



Schedule 6.4 continued

1 - 5	6 - 0	11 - 0	16 - 10000
2 - 30	7 - 0	12 - 0	17 - 10000
3 - 2	8 - 0	13 - 23	18 - 23
4 - 999	9 - 0	14 - 14000	19 - 14000
5 - 0	10 - 0	15 - 30	20 - 571.43

1 - 6	6 - 0	11 - 0	16 - 10000
2 - 14	7 - 0	12 - 0	17 - 10000
3 - 3	8 - 0	13 - 7	18 - 7
4 - 4	9 - 0	14 - 20000	19 - 20000
5 - 999	10 - 0	15 - 14	20 - 1000

1 - 7	6 - 0	11 - 0	16 - 1000
2 - 1	7 - 0	12 - 0	17 - 1000
3 - 5	8 - 0	13 - 1	18 - 1
4 - 6	9 - 0	14 - 1000	19 - 1000
5 - 999	10 - 0	15 - 1	20 - 0

DETAILED COSTING REFERENCE NUMBER 0.

1 - 6	14 - 0	27 - 0	40 - 0
2 - 15000	15 - 0	28 - 0	41 - 0
3 - 14000	16 - 0	29 - 0	42 - 0
4 - 13000	17 - 0	30 - 0	43 - 0
5 - 12000	18 - 0	31 - 0	44 - 0

6 - 12000	19 - 0	32 - 0	45 - 0
7 - 11000	20 - 0	33 - 0	46 - 0
8 - 0	21 - 0	34 - 0	47 - 0
9 - 0	22 - 0	35 - 0	48 - 0
10 - 0	23 - 0	36 - 0	49 - 0

11 - 0	24 - 0	37 - 0	50 - 0
12 - 0	25 - 0	38 - 0	
13 - 0	26 - 0	39 - 0	

1 - 2	14 - 0	27 - 0	40 - 0
2 - 8000	15 - 0	28 - 0	41 - 0
3 - 6000	16 - 0	29 - 0	42 - 0
4 - 3500	17 - 0	30 - 0	43 - 0
5 - 2100	18 - 0	31 - 0	44 - 0

6 - 1500	19 - 0	32 - 0	45 - 0
7 - 0	20 - 0	33 - 0	46 - 0
8 - 0	21 - 0	34 - 0	47 - 0
9 - 0	22 - 0	35 - 0	48 - 0
10 - 0	23 - 0	36 - 0	49 - 0

11 - 0	24 - 0	37 - 0	50 - 0
12 - 0	25 - 0	38 - 0	
13 - 0	26 - 0	39 - 0	

Once the project data has been written on disk, the program TRANSLATE can be used to find the integer linear programming formulation. Note that TRANSLATE does not solve the scheduling problem; it just puts it into a different form. TRANSLATE expresses the problem in terms of a cost function to be minimized subject to a set of linear constraints. In order to actually solve the problem, a large computer with an integer linear programming package must be used.

TRANSLATE was run on the project data with the following results, (Schedule 6.5).

#### SCHEDULE 6.5

##### COST

$C_0 + 0 S_{1,1}$   
 $+ 520 S_{2,1} + 600 S_{2,2} + 1400 S_{2,3} + 2500 S_{2,4} + 2000 S_{2,5} + 900 S_{2,6}$   
 $+ 36.6666667 S_{3,1} + 1750 S_{3,2} + 3750 S_{3,3}$   
 $+ 1000 S_{4,1} + 1550 S_{4,2}$   
 $+ 571.428572 S_{5,1}$   
 $+ 1000 S_{6,1} + 1000 S_{6,2} + 0 S_{6,3} + 1000 S_{6,4} + 1000 S_{6,5} + 1000 S_{6,6} + 5000 S_{5,7}$   
 $+ 0 S_{7,1} + 200 T_7$

##### CONSTRAINTS

T7 C = COMPLETION TIME

$S_{1,1} C = 0$   
 $S_{2,1} C = 1$   
 $S_{2,2} C = 1$   
 $S_{2,3} C = 1$   
 $S_{2,4} C = 1$   
 $S_{2,5} C = 1$   
 $S_{2,6} C = 1$   
 $S_{3,1} C = 12$   
 $S_{3,2} C = 1$   
 $S_{3,3} C = 1$   
 $S_{4,1} C = 3$   
 $S_{4,2} C = 2$   
 $S_{5,1} C = 7$   
 $S_{6,1} C = 1$   
 $S_{6,2} C = 1$   
 $S_{6,3} C = 1$   
 $S_{6,4} C = 1$   
 $S_{6,5} C = 1$   
 $S_{6,6} C = 1$   
 $S_{6,7} C = 1$   
 $S_{7,1} C = 0$

# Schedule 6.5 continued

-S 1, 1 -T 7 -S 7 1 -S 5 1 -S 2 1 -S 2 2 -S 2 3 -S 2 4 -S 2 5 -S 2 6 C= -41

T6 -T 7 -S 7 1 C=-1

-S 1, 1 -T 6 -S 6 1 -S 6 2 -S 6 3 -S 6 4 -S 6 5 -S 6 6 -S 6 7 -S 3 1 -S  
3 2 -S 3 3 C=-34

-S 1, 1 -T 6 -S 6 1 -S 6 2 -S 6 3 -S 6 4 -S 6 5 -S 6 6 -S 6 7 -S 4 1 -S  
4 2 -S 2 1 -S 2 2 -S 2 3 -S 2 4 -S 2 5 -S 2 6 C=-41

BREAKTHROUGH IN ACTIVITY 2

+S 2, 1 +S 2, 3 +S 2, 4 - 4 DL 2, 4 C =0  
2 DL 2, 4 -S 2, 5 -S 2, 6 C=0

BREAKTHROUGH IN ACTIVITY 2

+S 2, 5 - 1 DL 2, 5 C =0

6 DL 2, 5 -S 2, 6 -S 2, 7 -S 2, 8 -S 2, 9 -S 2, 10 -S 2, 11 C=0

BREAKTHROUGH IN ACTIVITY 6

+S 6, 1 +S 6, 2 - 2 DL 6, 2 C =0

5 DL 6, 2 -S 6, 3 -S 6, 4 -S 6, 5 -S 6, 6 -S 6, 7 C=0  
-C0 C= -33540

THE NUMBER OF VARIABLES IS 27

C0= V 1

S 1, 1= V 2

S 2, 1= V 3

S 2, 2= V 4

S 2, 3= V 5

S 2, 4= V 6

S 2, 5= V 7

S 2, 6= V 8

S 3, 1= V 9

S 3, 2= V 10

S 3, 3= V 11

S 4, 1= V 12

S 4, 2= V 13

S 5, 1= V 14

S 6, 1= V 15

S 6, 2= V 16

S 6, 3= V 17

S 6, 4= V 18

S 6, 5= V 19

S 6, 6= V 20

S 6, 7= V 21

T 5= V 22

T 6= V 23

T 7= V 24

DL 2, 4= V 25

DL 2, 5= V 26

DL 6, 2= V 27

THE NUMBER OF CONSTRAINTS IS 33

The first few lines give the direct cost function to be minimized. The variable  $CO$  stands for the minimum cost, which is defined by the final constraint. The first group of constraints gives the bounds for the reduction variables, referred to as  $S_{i,j}$  in the text. For example,  $S_{4,2} \leq 2$  and  $S_{4,1} \leq 3$ ; this is derived from the fact that the cost function for Activity 4 has two parts, one interval of length 3 and the other of length 4. Similarly, there are seven constraints of the form  $S_{6,j} \leq 1$  because the cost functions for Activity 6 has seven parts.

The next group of constraints specifies the precedence relations.  $T_7$  and  $T_6$  are introduced because Activities 6 and 7 have more than one precedent. The first constraint of this type, for example, is equivalent to  $T_7 \leq D_1 + D_2 + D_5 + D_7$ .

The next group of constraints fixes the breakthrough points in the project, as in equations (30) and (31), Chapter 5. There are two breakthrough points in Activity 2, at duration 5 and duration 6. There is one breakthrough point in Activity 6, at duration 12.

The final constraint defines the minimum cost as £33,540. It will be noted that this program does not take account of indirect costs. In order to solve the scheduling problem the matrix of coefficients of the cost function and the constraints must be given to an integer linear programming package. This might be done manually, however, it is clear that a more efficient method would be to have some kind of automatic interface between TRANSLATE on the PET and an integer linear programming algorithm on a large computer. Such an interface has not yet been created and will be the subject of further research.

## ii. Heuristic Formulation for a 7 Activity Project

The heuristic program was run on the project data and the results are given below. (Schedule 6.6).

As previously intimated, a detailed schedule of activities can be obtained for the first and last or, alternatively, all project durations. The former choice was made in this case.

# SCHEDULE 6.6

ACTIVITY NO.	DURATION	COST	ACTIVITY DESCRIPTION
1		.00	DUM
2	10	980.00	A
3	20	1560.00	B
4	17	10000.00	C
5	30	10000.00	D
6	14	10000.00	E
7	1	1000.00	END

## CRITICAL PATH

1 - 2 - 4 - 6 - 7

## PROJECT DURATION

## PROJECT COSTS

	INDIRECT	DIRECT	TOTAL
42	8400.00	33540.00	41940.00

SPEED ACTIVITY	COST INCREASE	PLUS ESTIMATE	RELAX ACTIVITY	COST SAVING	DURATION
2	520.00	.00			41
2	600.00	.00			40
6	1000.00	.00			39
2	1400.00	.00			38
6	1000.00	571.43			
6	.00	571.43			
5	571.43	.00			37
5	571.43	.00			36
6	1000.00	571.43			
5	571.00	.00			35
6	1000.00	571.43			
5	571.00	.00			34
6	1000.00	571.43			
5	571.43	.00			33
5	571.43	1000.00			
4	1000.00	.00			32
5	571.43	1000.00			
4	1000.00	.00			31
2	2500.00	.00			30
2	2000.00	.00			29
2	900.00	36.67			
3	36.67	.00			28
3	36.67	1036.67			
4	1000.00	1000.00			

4 1000  
3 36.67

## Schedule 6.6. continued

ACTIVITY NO.	DURATION	COST	ACTIVITY DESCRIPTION
1		.00	DUM
2	4	8900.00	A
3	19	1596.67	B
4	15	12000.00	C
5	23	14000.00	D
6	8	15000.00	E
7	1	1000.00	END

## CRITICAL PATH

1 - 2 - 3 - 4 - 5 - 6 - 7

PROJECT DURATION	INDIRECT	PROJECT COSTS DIRECT	TOTAL
28	5600.00	52496.67	58096.67

NO FURTHER REDUCTION POSSIBLE  
ALL CRITICAL ACTIVITIES AT CRASH DURATION

PROJECT DURATION	INDIRECT	PROJECT COSTS DIRECT	TOTAL
42	8400.00	33540.00	41940.00
41	8200.00	34060.00	42260.00
40	8000.00	34660.00	42660.00
39	7800.00	35660.00	43460.00
38	7600.00	37060.00	44660.00
37	7400.00	38631.43	46031.43
36	7200.00	39203.86	46402.86
35	7000.00	40774.29	47774.29
34	6800.00	42345.71	49145.71
33	6600.00	43917.14	50517.14
32	6400.00	45488.57	51888.57
31	6200.00	47060.00	53260.00
30	6000.00	49560.00	55560.00
29	5800.00	51560.00	57360.00
28	5600.00	52496.67	58096.67

RUN COMPLETED

The first schedule gives the minimum cost duration, which is 42 time units, and the critical path for that duration. This schedule is followed by a summary of the way in which the project duration can be progressively decreased until crash duration is reached. For example, in order to complete the project in time 37, it is necessary to speed up Activity 2 by 3 time units, and Activity 5 by 1 time unit. Notice that in some cases, it is necessary to speed up more than one activity in order to decrease the project duration, eg, to bring the project completion time from 38 down to 37 time units, it is necessary to speed up Activities 5 and 6. Activity 6 is speeded up by two time units because a point of zero slope on the time cost curve is encountered. The cost of speeding up the project in this way is £1571. There are, of course, alternative ways of speeding up the project (for example, speeding up 4 and 5 together; or 2 by itself) but all are more expensive. The minimum direct cost for the project is established as £33540.

It can be seen, therefore, that the heuristic model has arrived at an identical solution to the one established using the integer linear programming model(pp 42).

A manual check was run on this project and as expected, proved extremely laborious and time consuming. The tendency to make errors was extremely high and a series of checks was essential. The ultimate solution obtained, confirmed the results derived using the heuristic and integer linear programming models.

#### Format of Computer Outputs

A major requirement in the design of the computer systems was that outputs should be self-explanatory and it can be seen from Schedule 6.6 that this, to a large extent, has been achieved. The precise form and level of detail required from each output will, however, depend on the amount and level of information required by the decision maker. For instance, company directors may simply require information relating to direct and indirect costs for project durations ranging from minimum cost duration to crash duration. Planners, estimators and site managers may require much more detailed information, ie, a complete breakdown of detailed costing. The system has, therefore, been designed to permit the data to be structured in several different ways, depending on the amount of detail required. The output is concise, sifted and action orientated, ensuring that those who receive information and make the decisions receive only that part of the output which is relevant for their action. For example, the following basic information is available on the screen, the printer or both:

A full DATA LISTING - This can be obtained after running any of the three programs, INCRIT-T/C, AMCRIT-T/C and ANCRIT-T/C. Where the sole output required is a data listing, AMCRIT-T/C is run listing the data without, of course, amending the data in any way.

Abbreviated Output - This can be obtained using ANCRIT-T/C. The following output is given for the first and last projects durations only, activity number, duration, cost, activity description, critical path, project duration, project costs (direct, indirect and total). The only output given for intermediate project durations is the activity number (speeded or relaxed), and the cost (increase or saving). Finally, a summary is given of the project costs (direct, indirect, total), for each project duration.

Detailed Output - This can be obtained using ANCRIT-T/C. For every project duration, the following output is given: activity number, duration, cost, activity description, critical path, project duration, project costs (direct, indirect, total). Finally, a summary is given of the project costs (direct, indirect, total), for each project duration.

Amendments are input using AMCRIT-T/C. These changes are displayed on the screen as they are made. A full data listing of the new data input can then be obtained on the screen, the printer, or both.

#### Breakdown and Recovery Procedures

From the ultimate user's point of view, it is essential that a computer based production system can display a high level of reliability. This, in turn, will be dependent on the individual elements on which the system is based. It must, however, be accepted that all systems will break down or fail at one time or other and this possibility must be catered for. Frequency of system breakdown will vary from one computer configuration to another.

During the design of this system, it was considered that breakdowns would occur due to such factors as, loss of the complete data base, or section of it, loss or corruption of the operating system software, loss or failure of application programs, breakdown of the hardware components of the system, i.e. line printer, disk system or the central processing unit. One way of coping with breakdowns is to install a complete standby system so when a failure is detected, the processing can automatically be switched over to the standby system. This approach found little support with the sample companies, particularly in relation to site applications.



A cheaper and more acceptable alternative is to have compatible hardware available within the company as a whole to cope with emergencies.

It is interesting to note that no major breakdown of the hardware occurred during the research program. This experience would suggest that it would not be unreasonable to place a high level of confidence in the reliability of this type of system. The component most likely to break down is the line printer and in such an eventuality the VDU can, of course, still be used to input data and communicate the output to the user, allowing continuity to be achieved.

The probability of corruption of the data base can be substantially reduced or completely eliminated by keeping duplicate data files on separate disks, (disks are comparatively inexpensive). A commonly used arrangement, in terms of the data base, is to keep three different versions on floppy disk, often referred to as the Grandfather, Father and Son copies. The latest activities are processed against the last Son version of the data base. Successful completion of this work results in a new version of the Son copy. The original Son and Father versions become the new Father and Grandfather. The previous Grandfather version is discarded and the tape or disk on which this information was stored is re-used. The copying of data can, of course, take place out of normal working hours, thus ensuring that the computer is free for analytical work whilst production is taking place.

The main priority is, of course, to ensure continuity of the production work. The continuation of near normal working in the event of a breakdown (which is unlikely to be for more than a day), can be achieved by regularly producing printouts of the activity state. Whilst these printouts will not be up to date they will enable the users to continue to implement control procedures based on the current state of the plan. Even this reduced facility will still constitute a considerable improvement over the more generally used manual control procedures. It is often desirable in the early stages of implementing a computer based production system, to retain appropriate aspects of the manual procedure. This allows gradual implementation of the new system, increases the confidence of the user and hopefully, highlights its comparative advantages.

### Updating

It is impossible to make clear recommendations as to the frequency of updating for any particular project. Discussions during the course of this research programme, with planners and site managers, suggest that

at least a weekly update is desirable. It is considered, however, that the optimum frequency of updating of a project is a function of many factors including its size, number of major variations that occur throughout a project's duration and most important, the means of analysis available to site management. It can be seen that where a project is of short duration, frequent updates are desirable in that possible delays may cause a large percentage over-run in the expected completion time. Conversely, a large, long duration project is not as sensitive to a single delay in relation to a particular activity. In the latter stages it compares more with the smaller project and therefore becomes more sensitive in relation to possible delays on the final activities. From this, it can be seen that the stage of the contract and its size may well determine the frequency of update, i.e. shorter intervals near the end of a large project or for projects with a large number of variations, it is not unusual in practice for a thousand or more variations to occur on an individual project.

Discussions with the sample companies confirmed the general practice is to combine updating with monthly valuations, i.e. when information is required for financial statements. Although monthly updating was considered to be of little value to the site manager, the manual systems in use make more frequent updates virtually impossible.

It is evident from this research that the frequency of updating necessary, is closely associated with critical activities reflecting the need for more frequent decision making information by site management, where this type of activity is involved. Where the network is a linear one and activities are performed in sequential manner there will be very few parallel activity chains therefore the percentage of critical activities tends to be high. As a project moves towards completion the percentage of critical activities naturally increases until the final activity is reached when the project is said to be 100% critical. Updating periods should therefore match these high criticality situations thus providing the necessary control information.

On the other hand, medium and large size projects tend to have networks with many parallel activities, with a consequentially high number of interacting links. Initially the number of critical activities is low. However, as the work progresses the number of critical activities increase slowly, rising abruptly over the last quarter of the project duration, therefore, an updating interval that decreases in length toward the end of the project may be preferred. The computer based production system discussed is

designed to increase the ease with which updating can be undertaken thus enabling the site manager to respond quickly to the needs of his particular project. It can be seen that the interactive nature of the micro computer is particularly significant in this respect.

The results of the tests undertaken are seen as indicative of the flexibility and accuracy of the models postulated and their ability to satisfy the research criteria and objectives. An additional advantage emerging from the testing procedure is the ease with which alternative solutions can be pursued. This introduces a different set of decision rules, allowing the models to be used as a research tool as well as an operation program.

It is considered that these models aided by the computational power, low cost, and acceptability of the micro computer will allow problems to be formulated in a more rigorous manner than hitherto and provide solutions to problems that have not previously yielded to manual methods of analysis. They constitute therefore, a major factor in assisting construction management towards more realistic decisions.

## 7. SUMMARY AND GENERAL CONCLUSIONS

### 7.1 Decision Making (Chapter 2)

7.1.1 The general building scene is summed up quite aptly by Harper<sup>6</sup> who concludes that "we still, in the main, bolster up an organisational structure in which the contractor is usually obliged to adopt ill-founded time and financial programmes, to erect a project untried and untested by model or simulated studies ..... The power of decision is nearly always spread over several different interests and remote from the scene of operations". The picture emerging from the studies undertaken during this research is one of intuitive decision making based mainly on experience in a situation of uncertainty. Uncertainty in relation to work load, production methods, resource availability and profitability, amplified by the less than deterministic environment which usually surrounds the construction project itself. Organisations responsible for production are often criticised for poor management in terms of the optimal use of resources, inadequate planning and control procedures and an inability to determine accurately, project costs and duration times. The inability to appreciate the relationship between the time and cost parameters and model this relationship may be of even greater significance in terms of management decision making.

7.1.2 It is important to confine subjective decision making, often referred to as intuition or guesswork, to areas where "no better knowledge" exists, particularly where decisions are predictive in nature. Predictive decision making is widely practiced in the construction industry and highly expensive resources are often committed in this way. Each manager has the discretion to make certain decisions. It is however "the time span of discretion" between their implementation and the resulting outcome that determines the responsibility that the manager bears in his job. Decisions, once made, commit an organisation's resources. Accurate decisions where actual outcomes are as predicted will encourage efficient use of these resources, inaccurate ones obviously result in waste. However, without a method of evaluating a decision there can be no check on this and the organisation may well be sustaining unnecessary losses. What is really missing, therefore, is a quick and accurate method of analysis which enables accurate decisions to be made using criteria such as time and cost. There appears to be no lack of suitable data for this purpose. The use of decision analysis - "A logical procedure for the balancing of factors that influence a decision ....". (Howard)<sup>22</sup>, offers many advantages in analysing construction problems, it also has a number of disadvantages (see Section 2.4, Chapter 2).

## 7.2 Planning and Control

- 7.2.1 In many instances, the ability to plan and evolve effective control procedures may mean the difference between survival and liquidation/bankruptcy for many construction organisations and many, even the large ones, have been forced into liquidation due to the financial difficulties encountered on a single contract. It is considered that these difficulties could often have been anticipated and possibly avoided, had an adequate control and feedback system been in operation to provide early warnings to management.
- 7.2.2 As the time span of a plan increases its accuracy will tend to decrease accordingly. It is necessary to adjust plans frequently and to measure the effect of these adjustments on future events. There is a need, therefore, for a balance to be struck between relying totally on imperfect information and postponing a decision until perfect information is available. Continuous comparison of a project plan with actual performance enables the manager to instigate the control necessary for early correction of deviations.
- 7.2.3 The actual cost of planning must be balanced against the likely benefits to be obtained at the completion of a contract. It must, however, be emphasised that planning is not a luxury but a prime necessity for any organisation that wishes to operate effectively. The cost of planning must be offset against the cost of such things as false starts, the inadequate allocation and utilisation of expensive plant, equipment and labour that will inevitably result when planning has not been undertaken, ie, it must be judged against the losses that may be incurred if it is not undertaken. It must be remembered that planning is a means to an end and not an end in itself, and more effective ways of implementing and controlling the plan must be continually sought.
- 7.2.4 It is becoming more common for contracts to be awarded not purely on the basis of the lowest price but also on the ability to complete the work in the shortest time. It is important therefore, to ascertain whether the client's prime objectives are time or price, or a combination of the two, in terms of identifying the most acceptable tender. It should also be noted that in practice, the duration of a contract is not always directly related to its value.
- 7.2.5 The assumption that "the earlier site activities are commenced, the sooner the contract will be completed", must be avoided because in almost all circumstances the reverse is much nearer the truth. Failure to plan

carefully and accurately before work commences on site will invariably delay completion and result in additional costs. It is essential that the architect in his professional capacity is aware of the implications of this approach and guides his client accordingly. While the ultimate decision on a starting date will be influenced by the size and nature of the contract, nevertheless this general premise is applicable whatever the size of the contract.

### 7.3 Time - Activity and Project Durations (Chapter 3)

7.3.1 Costs are usually calculated in considerable detail, while the time for an individual activity or a project as a whole is often nothing more than "a gross estimate based on similar projects". This situation probably derives from the fact that despite the change in emphasis referred to in Paragraph 2.4 the success of a tender is still judged to relate directly to the competitiveness of the tender figure submitted.

7.3.2 Discussions with the sample companies suggest that the most significant single factor affecting activity duration is weather conditions. This factor is, however, often cited when the underlying cause relates to lack of adequate planning and control, nevertheless weather conditions do present a considerable problem and it is recommended that allowance is made at the end of clearly defined phases of a contract, e.g., after the ground works have been completed, with a special allowance for those individual activities identified as most likely to be affected by weather conditions. This, in no way, effects the models postulated in this research, as whatever the approach adopted, this can be accounted for in the evaluation of the precedence logic.

7.3.3 The findings of other researchers, particularly MacCrimmon and Ryavek<sup>37</sup> and Klingel<sup>39</sup> raises grave doubts as to the reliability and accuracy of stochastic models, such as PERT, when applied to the analysis of the time parameter. It is considered that many of these difficulties stem from an unsuccessful attempt to build simplicity into a sophisticated, probabilistic model. Bearing in mind the clear preference for deterministic "one time estimates" on the part of the planners and site management, it seems logical to conclude that the deterministic approach is certainly the most acceptable and probably the most appropriate for the majority of construction projects. Furthermore, it can be seen that the introduction of the cost parameter in an attempt to optimise the relationship, so complicates the issue as to make the use of probabilistic time estimates unrealistic. However, the models used do not preclude the use of multi-time estimates and such an approach could, for instance, be related to specific points on the time cost curve.

#### 7.4 Characteristics of Construction Costs (Chapter 3)

- 7.4.1 Costs not only vary from organisation to organisation but also from contract to contract within the same organisation - a conclusion substantiated in discussions with the sample companies. However, the fact that "there are certain factors that remain constant" whatever the situation did also emerge. This latter factor is suggested as being worthy of further research (Section 8.2).
- 7.4.2 Information required for costing, either for estimating or planning purposes, must be accurate and preferably based on work measurement reflecting the expertise of the particular company and should be easily retrievable. It is essential that actual production costs can be ascertained quickly and accurately during the progress of the contract itself and that planned and actual costs can be easily compared. The differences between actual results and the standard set requires careful analysis and may be expressed in the form of variances which would identify where the responsibility for such differences lie.
- 7.4.3 Action in high cost areas can often produce what appear to be immediate benefits, however an initial saving may in fact change the critical activities for the contract as a whole, with the result that characteristics of uncritical activities are changed in such a way that they, in turn, become critical. Such a variation may change the emphasis in terms of resource requirements necessitating a change of policy and, in the end, result in an increase in cost.
- 7.4.4 It is essential to the manager that the level of monitoring detail which should be reported is judged to be that which allows action to take place where and when the actual situation and the cost plan diverge. Information is required rapidly and in a form that is easily digestible. The monitoring system can be simplified and made more effective in two ways (a) delegation of authority and (b) reporting critical or key ratios only, using the exception criteria.
- 7.4.5 The majority of activities in a construction project fall logically under the heading of forecasting and these forecasts are generally time dependent or dynamic activities. It must be recognised therefore, that unless estimates are properly prepared and relate to time factors, the monitoring of costs and their comparison with estimates is often invalid. It is considered that efficient cost control is dependent on:

- i . the preparation of a realistic estimate expressed in terms appropriate to control once the contract is actually under way;
- ii . monitoring commitments entered into against original estimate;
- iii . detailed cost control of individual activities with particular emphasis on critical activities allowing the exception principle to be operated and closely relating time and cost (Section 3.5), in such a way as to optimise performance;
- iv . quick and effective feedback showing deviations from plan and highlighting critical activities;
- v . the rapid comparison of alternative courses of action allowing informed decisions to be taken quickly, based on objective information.

7.4.6 In the main, individual activity direct costs will decrease as the activity duration increases. The project duration is found by summing activity durations along the critical path. Conversely, indirect project costs will tend to increase with an increase in project duration. This increase will normally take place in a piecewise linear fashion.

## 7.5 The Time Cost Relationship (Chapter 4)

7.5.1 From discussions with the sample companies it can be concluded that the time parameter is carefully planned, often in considerable detail and controlled using networks or bar charts, etc. In addition, these organisations consider themselves to be cost conscious and confirmed that their major objective was to complete all projects at the least possible cost. They did not, however, give serious consideration to the relationship between these two parameters and its significance in terms of decision making. Accepting that for any activity or for any project there is a range of possible durations, their difficulty was to determine which duration should be selected in order to arrive at the optimum cost for an individual activity or for the project as a whole. As there was no adequate facility available their only recourse was to intuition and experience. There is no way in which the time cost relationship can be analysed in an intuitive way. In fact it is virtually impossible to identify the time induced critical activities in this way, let alone the significance of simultaneous variations in the time and cost parameters and the dramatic way in which this can change and increase the number of critical activities. The intuitive approach does not therefore represent a suitable basis for decision making. It is impossible to compute the variety of possible combinations manually for the highly complex set of activity relationships that exist in the normal construction project.



- 7.5.2 It is generally accepted that to decrease the duration of any project more money must be invested and this invariably implies the allocation of additional resources. What is not appreciated is that additional resources need only be allocated to critical activities, i.e. those that directly affect the overall project duration.
- 7.5.3 Indirect costs are particularly significant in situations where the early completion of a project will have a profound effect on the client's maximisation of his investment, e.g. completion of factory design to manufacture a new and more effective commodity such as micro computers. In this case, the later the project is completed, the smaller will be the client's short term or even long term share of the market. Factors such as this may be of considerable significance and may well warrant the crashing of a project even though the initial project cost is increased. It is necessary to balance these factors in order to achieve an optimum return on investment, and, therefore, to identify an optimal relationship between indirect costs and the duration of the project.
- 7.5.4 Early researchers considered the time cost parameters in isolation. Subsequent attempts to relate the time and cost parameters produced models that were extremely rigorous necessitating highly efficient computational facilities normally available only on the most high powered computers. These models assume bounded piecewise, linear continuous convex and non increasing functions and accordingly use standard linear programming methods for their solution. Construction activity cost curves however, regularly violate this assumption in that they assume any form that is bounded and non increasing, thus the value of this type of model is very limited. Integer linear programming methods were used to handle the more complex trade off functions for varying configurations of the cost curve. The models suggested using this approach generated an even greater number of constraints and variables whereby an extremely high level of computer analysis was required even to cast the problems in an appropriate form, prior to its analysis with a corresponding increase in the risk of error. Attempts to use dynamic programming also proved unsuccessful in that this approach can deal only with pure combinations of sequential and parallel links making it totally unsuited for modelling construction projects where the complex interrelationship and interdependency of the activities are an integral feature of the problem.

## 7.6 Integer Linear Programming Models (Chapter 5)

### 7.6.1 Any continuous curve can be approximated by a piecewise linear curve.

The accuracy of the approximation depends only on the lengths of linear segment chosen. The problem of finding minimum project costs in cases in which the project cost curve for each activity is piecewise continuous and totally defined in the interval between crash duration and minimum cost duration is solved in Section 5.2 by finding piecewise linear approximations for the time cost functions,  $C_i(D_i)$  then replacing each piecewise linear approximation by a set of conditions given in equations 14, 15, 16, 17, 18 and 19, allowing the problem to be solved finally, using standard methods of integer linear programming.

### 7.6.2 The problem of solving minimum project cost when the time cost relationship is only partially defined is a much more general one and can only be dealt with by using an integer linear programming approach of the type defined in Chapter 5, Section 5.3. This solution is theoretically acceptable but is difficult to implement in practice due once again to the large number of variables and constraints and can only be solved using a micro computer for comparatively small networks. There will always be a qualitative similarity between the overall project time cost curves and the time cost curves associated with individual activities. Whatever the level, the time cost relationship always displays a distinctive pattern and is never simply linear.

### 7.6.3 One of the distinguishing characteristics of time cost curves is that commencing from the minimum cost duration. It becomes progressively more expensive per time unit to expedite the project or activity in terms of direct costs. This characteristic continues until a certain breakthrough point is reached, at which point the cost increase slope drops dramatically and may even reduce to zero. Beyond this breakthrough point the cost of expediting the project again increases progressively until a further breakthrough point is reached. A significant feature is that for any particular time cost curve there are very few breakthrough points relative to the number of durations. Sometimes after a breakthrough point has been reached there is a discontinuous jump. Errors of zero slope occur where a reduction in duration does not result in corresponding increase in cost. These areas can, therefore, be discounted when analysing the network as the situation is basically unstable. This can be attributed to the fact that activity data at this point is unreliable and consequently a slight change in data will produce a radical change in the speeding up strategy

for the project as a whole. This instability explains some of the difficulties encountered in using integer linear programming models and particularly, the difficulties of implementing them in practice.

7.6.4 When the integer linear programming model is based on points of breakthrough on the cost curve, undefined and defined points on the curve can be dealt with in a uniform way. In addition, and most importantly, the number of integer variables introduced is less, since the number of breakthrough points is less than the number of points of discontinuity. The fact that less integer variables are used means that there is less chance of possible non convergence. The basic difficulty of instability near breakthrough points remains however.

## 7.7 Heuristic Models (Chapter 5)

7.7.1 Theoretical models based on integer linear programming have a number of limitations:

- i. The preliminary analysis necessary to derive a set of constraints from the network and the time cost data for each activity is complex and laborious. The ability to undertake this type of analysis requires a level of skill and understanding that cannot normally be expected from the average user.
- ii. The computational process related to integer linear programming is inherently complex due to the large number of constraints and variables and thus a large computer is required to deal with this aspect effectively. This would not be in line with the aim of this research project in relation to the real values of micro computers in terms of flexibility and cost.
- iii. Although sophisticated in their mathematical development, the models presented could be unreliable when - as is often the case - there are a large number of variables and constraints. This is due to the stochastic behaviour of the two random data input variables, the fact that they may or may not be stochastically dependent and the complex nature of the analysis being undertaken.
- iv. The potential industrial or professional user "will reject out of hand any over sophisticated mathematical model". This view was the general one emerging from discussions with the sample construction companies consulted and confirmed by research work undertaken by Arditi<sup>r</sup>.

It is possible, however, to cope with the problems associated with non linear time cost curves and, at the same time, take advantage of the low cost computational and analytical skills of the micro computer by evolving a heuristic solution to the problem.

- 7.7.2 For a high percentage of activities only minimum costs and minimum cost duration data will require analysis and it can be concluded from a study of existing data that as high as 90% of the activities in a construction project will have piecewise linear time cost curves with no more than three pieces. The heuristic models developed in this research take this factor into account.
- 7.7.3 The ability to phase projects is welcomed by both planners and contract management and networks of approximately 100 activities are considered to be appropriate and easy to handle. As long as the difference between the crash duration for the phase and the minimum cost duration is less than fifty time units this process of phasing can be repeated indefinitely.
- 7.7.4 The interdependency of phases may be linear or tree-like or possibly even more complex. In the latter cases it will not be possible to run through a project from beginning to end substituting activities for phases. However this can be dealt with without difficulty by running certain of the phases in isolation until the interdependency is again a linear one.

## 7.8 Computer Based Production Systems (Chapter 6)

- 7.8.1 It is not possible to cope manually in computational or analytical terms with the time cost relationship problem for other than the smallest projects. These requirements can only be dealt with by the use of an electronic computer due to its ability to:
  - i. digest vast quantities of data and perform many calculations in a very short time;
  - ii. process and analyse data far more accurately than manual methods and can be programmed to check itself for error;
  - iii. free management and other staff from time consuming, repetitive and often boring tasks allowing them to concentrate their attention on decision making relating to critical activities.

The design of a computer based production system must take account of the following general criteria:

- i. The system must meet the requirements of the potential users and the temptation to design and implement a sophisticated system which is not understandable must be avoided.
- ii. The system should make as much use as possible of the exception principle, highlighting deviations from expected behaviour, thus keeping the amount of routine information to an absolute minimum, although this must be available for checking if required. It must be borne in mind that the manager would not have time to interpret and analyse a large volume of information. Although the hard copy output should be available this should be reduced to a minimum and as much use as possible made of visual display units. It is important to produce different outputs to meet the needs of the various users, e.g. contract managers, planners, directors, who should be consulted as to the most suitable format.
- iii. The computer's electronic data processing system provides information only by transforming the data input. The accuracy of this information is dependent on the availability of pertinent data, which must normally be input in a specified format. It is important therefore, that the technique used to enter the data is accurately described and it is necessary to have a general data validation procedure which will check and reject unsuitable information, i.e. the system should request the operator to re-enter incorrect data items or enter missing data. It is important to ensure that existing data is not inadvertently destroyed when new data is entered.
- iv. The programme should be designed in such a way as to allow additional modules to be added at a later date. It is also considered desirable to relate production based computer systems to other aspects of the company's work. This is, however, difficult in practice bearing in mind the limitations of, for instance, the Bill of Quantities for planning and control purposes and has been disregarded for the purposes of this research.
- v. The levels of skill, and responsibility of the ultimate users should be taken into account, particularly in an interactive system such as the one suggested in this research, in that the user may have to retrieve information from the system and input new or modified information as appropriate.

## 7.9 Computer Hardware and Software (Chapter 6)

7.9.1 The micro computer offers a number of advantages over large central computers, particularly in terms of overcoming the resistance to the latter encountered in the construction industry, viz:

- i. Low capital cost - no additional running costs are incurred for computer time, telephone charges, etc. Running costs are therefore very low and maintenance minimal. No maintenance was necessary at all on the system used in this research.
- ii. An "on site" computer would generally be treated as a fixed "overhead" therefore its cost does not increase with use - conversely the cost of a remote computer does increase with use.
- iii. The interactive "user friendly" image generated by this type of computer helps to break down resistance to computer usage.
- iv. The possibility of rapidly updating plans is appealing to a busy site manager faced with continual amendments and variations in design, resource availability and production schedules.
- v. An on site micro computer would be personal to site management, allowing them to amend and control their own plans without interference from senior management operating from Head Office.

7.9.2 The CBM 32K combined with a dual drive floppy disk system and a high speed printer is capable of dealing with the full requirements of the heuristic model described in Chapter 5. The total cost of the system used in the research is extremely low at £2140. As was the case with hand calculators it is reasonable to conclude that substantial improvements and developments in micro computers are likely to occur in the next ten years with a consequent improvement in the ease and effectiveness with which the heuristic models suggested can be implemented. The 32K micro computer used will not however, cope, at the present stage of development, with the more demanding computational requirements of the integer linear programming models for other than the smallest projects. Further research is required on the interface between the micro computer and the main frame in this respect.

7.9.3 In terms of the speed with which a program can be executed BASIC is one of the slower languages. However, bearing in mind the ease with which it can be written, the ease with which "bugs" can be identified and the fact that protection of the ROM fail safe coding is often lost when, for instance, a machine language is used. BASIC is considered to be an appropriate language. A further important factor in relation to implementation is the ease with which minor adjustments can be made to the program

by personnel with only rudimentary knowledge of BASIC. There is, of course, no reason why the program cannot be converted to a machine language if this was considered desirable and appropriate.

7.9.4 The main challenge is "to provide a general purpose model that can accept continuous changes with a high degree of flexibility". The software designed to meet this challenge is described in Section 6.4, Chapter 6. The nature of the construction process is such that changes in plan are inevitable. Planning in this situation is "imperfect" in nature with new perspectives continually emerging. Emphasis in terms of the detail to be embraced should, therefore, concentrate on the immediate future in that this type of forecast can be made with much greater accuracy.

#### 7.10 Evaluating and Testing the Models (Chapter 6)

7.10.1 Criteria such as "what constitutes a good solution" depends to a large extent on each organisations's and/or individual project's requirements, ie, in one instance, meeting the target completion date for a project may be very important. In another, minimal cost or holding within resource constraints may be of greater significance. The quality of the solution is only one of several criteria requiring attention. Such features as computational efficiency and simplicity and the ability to adequately reflect practical situations, will be of considerable significance.

7.10.2 Due to the unavailability of equipment and the time scale involved it is not possible at this stage, to pursue what might be considered as the ultimate test in terms of the applied potential of the system, by means of practical field tests. While accepting the logic of this method of testing, it does suffer from two major disadvantages, the lack of breadth and depth available in any one or a limited number of ongoing projects, both of which are essential features in testing the ability of the model to cope with a full range of time cost relationships. It is considered, therefore, that the use of data that simulates a wide range of complex interrelationships, overcomes these difficulties and therefore represents an appropriate method of evaluating the potential of the models. Prior to final implementation, the models should, of course, be tested in construction companies. It is considered that such tests should extend over a period of eighteen months. This final stage is seen as an extension of the research and is therefore included under "Further Research" (Section 8.2).

7.10.3 In the case of the integer linear programming model once the data has been written to disk, the program TRANSLATE can be used to find the integer programming formulation. This program does not, however solve the scheduling problem, it just presents it in a different form, expressing the problem in terms of cost functions to be minimised subject to a set of linear constraints, allowing it to be solved by the microcomputer. It is possible, however, to compare the integer linear programming model outputs with the heuristic model for a small project thus providing a check on the accuracy of one against the other.

In the case of the comparative test described in section 6.5, Chapter 6, for a 7 activity project, the solutions in terms of minimum cost were identical. It can be concluded, therefore, that the heuristic model, although adopting a simpler method of analysis is capable of providing a solution of a comparable level of accuracy. It can also be concluded from the tests on the 74 activity project (section 6.5) that as the time cost curves become more complex and the project is speeded up, the number of critical activities increases and the critical paths elaborate accordingly.

7.10.4 An essential feature of computer aided systems is that outputs should, in as far as it is possible, be self explanatory. However, the precise form and level of the detail required from each output will depend on the amount and level of information required by the decision maker. For instance, company directors may simply require information relating to direct and indirect costs for project durations ranging from minimum cost duration to crash duration. Planners, estimators and site managers may require much more detailed information, eg, a complete breakdown of the detailed costing and related time parameters.

The system suggested in this research has been designed to permit the data to be structured in several different ways depending on the needs of the recipient, ie, the person who makes the decisions receives only that part of the output that is relevant to their action. Therefore an abbreviated output, a detailed output and a full data listing can be obtained from the system.

7.10.5 A very significant aspect of the system design relates to the ease with which amendments can be input. The program designed for this purpose, (AMCRIT-T/C) is formulated in such a way as to allow new data to be added without destroying the existing data base, thus enabling the logic of alternative strategies to be examined at any stage.



## 7.11 Updating, Breakdown and Recovery Procedures (Chapter 6)

- 7.11.1 The common practice of equating updating periods with monthly valuations is, in the main, a valueless exercise in terms of project control. The type and nature of the contract, its duration and complexity will all be significant factors in determining periods of update. It is clear that the shorter the period of forecasting the more accurate will be both the input and output. The system is therefore designed to encourage frequent updating. The frequency with which updating is undertaken is also closely associated with the complexity and multiplicity of critical activities and the consequent need for decision making information where these situations are evident.
- 7.11.2 Although, it could be concluded that due to its reliability in terms of this research programme, the hardware used, justifies a high level of confidence, it must be accepted that all systems will break down or fail at one time or other and such a possibility must be catered for. Breakdowns may occur due to such factors as loss of the complete data base or a section of it, loss or corruption of the operating system software, loss or failure of the application programs and breakdown of the hardware components of the system, disk system or the central processing unit. The possibility of corruption or loss of the software can be substantially reduced or completely eliminated by keeping duplicate data files on separate disks, (disks are comparatively inexpensive). The component most likely to breakdown is the line printer. However, should this occur, the VDU can still be used to input data and communicate the output to the user, thus allowing continuity to be achieved. In addition, hard copy output schedules should be kept sufficiently up to date to cater for short term break-downs.

## 8. FINAL CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

### 8.1 Final Conclusions

Decision making in the construction industry is mainly intuitive, based on experience in a situation of uncertainty in relation to work load, production methods, resource availability and profitability. Predictive decision making is widely practiced and highly expensive resources are often committed in this way. The most consistently quoted reason for this approach is the lack of a quick and accurate method of analysis to enable objective decisions to be made on factors such as time, cost and their interrelationship. These two parameters emerge as the most significant factors involved in management decision making.

Methods of planning these parameters are usually rudimentary in nature and rarely extend to embrace the more detailed requirements of short term planning. In practice it is necessary to adjust plans frequently to enable the continuous comparison of the plan with actual performance to take place and control procedures to be implemented to cope with deviations. It is quite clear that as the time span of planning increases, its accuracy will tend to decrease correspondingly. The cost of planning at all stages of a project must always be judged against the potential losses that may be incurred if it is not undertaken. Such judgements are, however, mainly subjective in nature and the cost of planning, particularly when computers are required, is often considered to be prohibitive.

Insufficient attention is given to the analysis of the time parameter at the pre-tender stage due, in the main, to the fact that "the success of a tender is judged to relate directly to the competitiveness of the price submitted in the tender figure". This lack of attention to the time parameter continues throughout the life of the contract and is particularly apparent in the failure to formulate effective short term plans.

Many researchers question the value, reliability and accuracy of probability time estimates and it is considered that many of the difficulties stem from an unsuccessful attempt to build simplicity into a complex probabilistic model. Few practitioners have a feel for the mathematical summing of probabilities, most prefer one time estimates, and consider that real life occurrences are seldom in random order or to measureable odds.

Costs vary not only from organisation to organisation but also from contract to contract within the same organisation. Concentration on high cost areas may produce what appear to be immediate cost benefits. However, when applied to non critical activities this approach will simply increase resource requirements resulting in an increase in costs with no consequent reduction in project duration.

The optimisation of the time cost relationship can be of great significance to the client in highlighting the effect of the early completion of a project on the maximisation of his investment. Construction management can also see the value of analysing and seeking an optimum or near optimum solution to the time cost relationship problem. However, this cannot be accomplished manually due to the range and variability of the highly complex activity relationships that exist in a construction project and the lack of suitable analytical models. Earlier attempts to model the time cost relationship failed due to the complexity of the models produced and the consequent need for high levels of computational power available, only on the large main frame computers, to solve them.

Although theoretically viable, the integer linear programming models suggested in this research suffer to an extent from this same problem due to the high number of variables and constraints involved. The number of integer variables can be reduced by concentrating purely on breakthrough points on the cost curve, since the number of breakthrough points is less than the number of points of discontinuity. However, the number of variables and constraints involved is still relatively high. It is concluded therefore that the answer lies in the development of heuristic models that can solve the problems associated with non linear time cost curves, at the same time taking advantage of the low cost, interactive nature and the computational and analytical skills of the micro computer.

The heuristic model postulated in this research exploits the advantages of the micro computer and although adopting a simple and more direct method of analysis to derive project cost curves, it can be concluded from the tests undertaken that the results obtainable are demonstrably comparable, in terms of accuracy, with the more precise integer linear programming models. The model also retains and integrates the role of managerial judgement essential to the construction process and so highly prized by construction management, thus allowing it to be viewed more as a valuable aid than as a potential replacement for the decision maker. It can be concluded therefore that the concept of optimality although achievable in strictly mathematical terms (it must be remembered that an element of mathematical accuracy is

is sacrificed in heuristic models), may not be of major significance or even desirable from the viewpoint of the practicing construction manager. Near optimality may well be a more appropriate and socially acceptable concept for project evaluation.

The outputs obtained using the micro computer meet user requirements in respect of the precise form and level of detail required by decision makers operating at different management levels by allowing the output to be obtained in both abbreviated and detailed form, including a full data listing where appropriate. The input can be simplified where only approximate solutions are required with a consequent effect on computational limits and speed of decision making. Amendments can be easily input into the system without destroying the existing data base thus enabling the logic of alternative strategies to be examined at any stage and the consequences involved in changes of plan to be evaluated.

It could be concluded that the deterministic framework assumed in the models precludes consideration of factors that are probabilistic in nature, e.g. weather conditions, multi time estimates, breakdowns or unavailability of plant or other resources. This is not the case and probabilistic factors can, in fact, be built into the models. The models however, do not in themselves cater for the analysis of these factors. The choice to include or not to include them is therefore a matter for the individual decision maker.

Finally, and it may seem a contradiction in terms, by enabling time and cost to be related and an optimum solution to be obtained, the models allow the decision maker to finally evaluate decisions in purely monetary terms - "the only criteria readily acceptable to construction management", who see the final outcome as "the optimisation of profits". This final conclusion is substantiated by Howard<sup>22</sup> who makes the point that "A good decision is a logical one .... one based upon the uncertainties, values and preferences of the decision maker. A good outcome is one that is profitable or otherwise highly valued....., we find no better alternative in the pursuit of good outcomes than to make good decisions".

## 8.2 Recommendations for Further Research

The body of the thesis refers to the significance of indirect costs and the variable approaches adopted in practice to ascertain the level of this type of cost parameter. However, although alternative approaches for obtaining realistic data are suggested it was not possible to pursue them in any detail due to the time scale involved. It is, therefore, recommended that further research should be undertaken into methods of ascertaining, reporting and allocating indirect costs in the construction industry.

The computing power and flexibility of the micro computer (Commodore have recently introduced a 96K micro computer), is increasing at a phenomenal rate. A point may soon be reached whereby the integer linear programming model suggested in the research, particularly those concentrating on breakthrough points on the cost curve may be solveable using micro computers. It is therefore recommended that developments in this field are kept under continuous review and additional research undertaken accordingly.

The "acid test" for time cost models such as the ones postulated in this research relate to their ability to satisfy the needs of practicing managers. Due to the time scale involved it was not possible during the research programme to undertake long term implementation studies, hence the use of simulated projects. It is therefore recommended that further research be undertaken to ascertain the practicality of the models suggested and their value and accuracy in relation to the decision making process and explore the level of user resistance/conflict attributable to the use of interactive micro computer systems on construction sites.

The minimisation of project duration and cost is inextricably linked with resources. Construction projects require the sequencing of well defined activities and are often characterised by capacity limitations on particular resources. It is therefore necessary to formulate the problem that emerges when explicit or inexplicit resource constraints affect the minimisation of costs and the achievement of a given project completion date. It is recommended therefore that the work undertaken on time cost optimisation be extended to include variable resource constraints and an application has already been made to the Science and Engineering Research Council for support for this additional research project.

Many practicing managers consider the cost of planning to be prohibitive and feel that it is not reflected in the results achieved in practice. There is little or no published information available to support or disprove this view point. It is recommended that research be undertaken to establish the real costs of this function including a comparative study of the potential losses that may result when formal planning and control procedures are not undertaken.

In assessing the level of confidence that can be placed in heuristic models it is useful to compare these with more sophisticated models such as those using integer linear programming methods. It is recommended that further research be undertaken to establish an appropriate interface for a range of models, between main frame computers and micro computers.

It was concluded, as a result of this research, that costs vary from contract to contract and from organisation to organisation. There are, however, certain cost factors that remain constant. It would be of value to undertake further research to substantiate this latter viewpoint in order to identify cost factors that behave in this way.

1. Operating Area
2. Company Structure
  - a. International
  - b. National
  - c. Regional
  - d. Group
3. Company Turnover
  - a. International
  - b. National
  - c. Regional
  - d. Group
4. Main Activities

(Housing, Industrial, Commercial, etc. reinforced concrete, system building, etc. multi-storey, low rise, etc.)
5. Appointment of Senior Staff
  - a. Internal
  - b. External
6. Tendering Procedures
  - a. Marketing
  - b. Time factor
  - c. Bidding Strategy (Knowledge of competitors)
  - d. Structure for dealing with tenders
  - e. Are overheads included in rates
  - f. Method of arriving at mark-up
  - g. Mark-up variances
  - h. Staff involved in final decisions
7. Planning Procedures
  - a. Pre-tender
  - b. Contract
  - c. Short term
  - d. Staff involved (Site Agent, Contracts Manager, etc.)
  - e. Sophistication, i.e. networks, time cost analysis, resource scheduling, simulation models.
8. Plant Policy
  - a. Plant hired or owned (Basis for purchase, i.e. 100% utilisation)
  - b. Method of charging to contracts (Internal hire rates)
  - c. Involvement of plant manager/specialists at
    - i. Pre-tender stage
    - ii. Contract period
  - d. Selection
  - e. Replacement
9. Cost Planning & Control
  - a. Contract as a whole
  - b. Specific activities

10. Decision Centres

a. Marketing - role of:

- i. Board of Directors (National)
- ii. Board of Directors (Regional)
- iii. Senior Estimator
- iv. Senior Planner
- v. Senior Contracts Manager
- vi. Site Agent
- vii. Plant Managers
- viii. Other

b. Tendering (tender figure) - role of:

- i. Board of Directors (National)
- ii. Board of Directors (Regional)
- iii. Senior Estimator
- iv. Senior Planner
- v. Senior Contracts Manager
- vi. Site Agent
- vii. Plant Managers
- viii. Other

c. Planning - role of:

- i. Board of Directors (National)
- ii. Board of Directors (Regional)
- iii. Senior Estimator
- iv. Senior Planner
- v. Senior Contracts Manager
- vi. Site Agent
- vii. Plant Managers
- viii. Other

d. Plant (Differentiate between purchasing and selection policy)  
Role of:

- i. Board of Directors (National)
- ii. Board of Directors (Regional)
- iii. Senior Estimator
- iv. Senior Planner
- v. Senior Contracts Manager
- vi. Site Agent
- vii. Plant Managers
- viii. Other

11. Time Cost Relationships

a. Company objectives

b. Conflicting or contradictory objectives of decision makers  
e.g. Plant Department maximise profit within budget - justify existence

Planners - minimum completion time - internal plant less efficient  
Estimators - lowest cost

c. Optimum solution in terms of time/cost may not coincide with objectives of various decision makers, e.g. ideal versus available emphasis on overall problem, i.e. problems components may be less than optimal,

12. Communication of decisions

- a. Higher - lower - instruction
- b. Lower - higher - information

13. External Factors Influencing Decision Makers

e.g. economic situation, market, labour availability, etc.



Company A1. General

The group is an international one with a wide spectrum of interests including building, civil engineering, mechanical engineering services, design services and building materials. There are therefore within the group a number of very large individual companies.

Total turnover is in the region of £400m, £300m of this figure being attributable to building activities.

2. Autonomy

The building division in the U.K. is subdivided into fourteen regions each of which has a turnover in the region of £25m. Each region is to a large extent autonomous, making decisions on which contracts to tender for up to a limit of £2m.

3. Main Activities

The division engages in a wide range of activities embracing work in the private and public sectors, including industrial, commercial and domestic work. Contracts are obtained generally by open tender or negotiation, speculative housing development is not undertaken. Management fee contracts and package deals involving the company's own design teams are also undertaken.

4. Appointment of Senior Staff

Company policy is geared in the main to development of potential within the organisation. Appointments are, however, made at senior level from time to time from outside where essential categories of experience do not already exist within the organisation. Promotion between regions and from region to division and vice versa is therefore common.

5. Tendering Procedures

Both a centralised and decentralised, i.e. regional, marketing function is included in the organisation. The identification of appropriate market areas is therefore dealt with at both regional and division level. Staff are not normally specifically qualified in marketing, this function being undertaken by senior staff with general building experience. Decisions to

tender are normally made at regional level, the final decision being taken by the Regional Director. The procedure, however, varies with the type and size of contract and where the tender figure exceeds £5m., the Executive Director of the Building Division is normally consulted. Divisional interests are represented by the Director of Estimating.

Prime Cost Tender figures including preliminaries and the recommended mark-up are normally prepared at regional level. The Director of Estimating is not normally involved where the tender is less than £2m. The tender figures quoted are given as a guideline only, many other relevant factors being taken into account. The objective is, however, to give as much autonomy to the regions as possible in this respect.

The overall procedures adopted and staff involved in the preparation of a tender vary with the size and/or complexity of the contract and the time available for the preparation of the tender, (usually in the region of six to eight weeks for competitive tenders). Wherever possible those staff with ultimate responsibility for the management of the contract are involved at this stage.

## 6. Planning Procedures

In all cases pre-tender planning forms the basis for the preparation of the tender figure. The degree of sophistication indulged in varies once again with the type, size and complexity of the contract being considered. It is interesting to note that contrary to the situation existing in many firms the estimating and planning departments work in close collaboration. Bar charts are the main medium used to communicate the pre-tender plan, although in certain cases these are supplemented by cascade charts to show inter-relationships. When a tender is successful, the pre-tender plans are then used as a basis for the more detailed planning procedures adopted for contract planning. CPM and/or bar charts are used to communicate information to the production site. Whenever possible site management play a significant role at this stage, one reason being to ensure their commitment to the planning decisions.

It is felt that the accuracy of planning is seriously affected by the lack of essential information from the design team. Subcontractors for instance are often a completely unknown quantity and yet their performance is often critical to the achievement of the target duration. The unavailability

of working drawings and cost information at crucial points is also quoted as major inhibiting factors to the accuracy of both time and cost planning. Considerable thought is given to the planning of both time and cost but although aware of the significance of the inter-relationship between these two factors little or no attempt is made to optimise this relationship. The time consuming nature of such an exercise is stressed, particularly the difficulties of updating and the effect of imperfect and inaccurate information from the design team.

#### 7. Plant Policy

Due to the size and extensive interests of this organisation, the policies adopted in the use of plant vary considerably. Plant is available internally, being supplemented by hiring in whenever necessary. The method of charging to contracts is also subject to wide variances.

It is considered that decisions relating to the selection of plant are best made by site management in consultation with plant specialists. Here again the practices vary and a more detailed examination of the procedures may be necessary at a later date.

#### 8. Cost Planning and Control

This organisation operates an extremely sophisticated set of procedures for recording cost information. The system of feedback and the way in which such information is available for managerial decision making is not clear, however the task of establishing time/cost relationships is considered to be extremely complex and the cost involved prohibitive. It is apparent, however, that the information required is in fact already available within the organisation in various forms.

Company B

- 1 The group is a national one operating under the control of a Holding Company. The group turnover is in the region of £46,000,000, £30,000,000 of which is concerned with construction work.

The construction division is further sub-divided into five smaller companies. Three of these are concerned with general construction work, one with house building and one with plant hire.

2 Autonomy

Each of these companies has its own organisation structure, which is to an extent autonomous, in that decisions on contracts up to £1,000,000 in value are made without reference to the Holding Company.

3 Main Activities

The three companies concerned with general construction work were involved in a broad spectrum of activity and were prepared to diversify within the limits of resource availability. The company concerned specifically with house building was involved with competitive or negotiated tenders and did not undertake any work of a speculative nature. All of these companies were involved from time to time in package deals involving their own architects or in collaboration with consulting architects.

4 Appointment of Senior Staff

Company policy in the main encouraged the development and promotion of senior staff from within the organisation. However the policy of growth and the willingness to diversify created a need from time to time for expertise that did not exist within the organisation. In these circumstances appropriate staff were appointed from outside the organisation.

5 Tendering Procedures

There existed both a centralised and decentralised marketing function. The centralised function tended to be informal and advisory in nature only. The marketing function was dealt with by staff with a general building background, no specialist marketing staff were employed.

The final decision as to whether or not to tender for contracts up to a value of £1,000,000 were made by the Managing Director of the company concerned after full consultation with his co-directors and senior members of staff in the organisation. Factors affecting the decision to tender took into account geographical location, size, capital budget, turnover and profit margins set by the Holding Company (construction company required to contribute 1% of its turnover to the

Holding Company) and the specific nature of the work to be undertaken i.e. multi-storey, industrial etc.

There was no formal quantified commitment to bidding strategy therefore the knowledge of competitors related to previous experience and intuition. In fact such knowledge was not considered to be particularly significant in that competitive tendering usually involved organisations very similar in calibre. The point was also made that in many instances, companies were short listed and interviewed by the client or his representative. The view was also expressed that there was insufficient time at the pre-tender stage to undertake sophisticated job analysis.

The company did not indulge in the practise of giving cover prices, when for various reasons the contract was considered inappropriate to the expertise of the company. The decision not to tender was conveyed directly to the client or his representative giving reasons. It was normal practice for the construction company concerned to justify such a decision at divisional level prior to finally contacting the client.

Responsibility for the preparation of the tender rested with the company estimating director. Overheads were not included in the bill rates but were presented as a separate figure. The mark-up varied from contract to contract and took into account such factors as previous experience with the client, architect or quantity surveyor - a decision not to tender was made where previous experience of the design team concerned had shown them to be inefficient - delays in settling variations and final accounts, resource availability, current work load and the possibility of further work in the future.

There did not appear to be close collaboration at this stage between estimators (cost) and planners (time).

## 6 Planning Procedures

The degree of sophistication indulged in at both pre-tender and post-tender stages was very much at the discretion of the individual company concerned. Limitations imposed at the pre-tender stage related to the time available for preparation of the tender, the estimated value of the contract itself, the cost of the planning procedures, current work load etc.

More attention was given to post contract planning and was dependant to an extent upon the complexity and cost of the job concerned. Although time and cost were identified, little attention was given to the relationship between these two factors. Particular attention was given to the scheduling of information required from the design team, e.g. availability of drawings, detailed specifications etc.

It was considered important to involve those responsible for production at the planning stage therefore contract managers were almost always involved at this stage. The involvement of site agents depended to a large extent on the size of the contract and their availability. Other specialists, such as the plant manager were used in an advisory capacity only. It was considered that decisions on plant selection and

utilisation were best made by production management, due to their specialist knowledge of the overall methodology to be used.

Both planning and the updating of control information was generally undertaken manually, little or no use being made of the computer facilities. The computer was, however, used fairly extensively for such things as wages, payment of invoices, etc.

#### 7. Plant Policy

The plant company previously mentioned operates as a completely independent hire company with its own objectives, including the requirement to operate at a profit. Preferential rates are however given to other companies in the division.

Plant specialists are only involved in taking decisions at pre-tender or post contract stages, at the discretion of the construction company concerned. Their role in terms of the production process being advisory in nature only. However, all decisions relating to the purchase of plant, maintenance procedures etc. are taken by the plant company and are not directly influenced by the specific needs of the construction companies within the division.

#### 8. Cost Planning and Control

The view was expressed that the overhead costs of implementing a sophisticated control procedure were high and might not be balanced by a resultant increase in profits.

## QUESTIONNAIRE

## APPENDIX 4

<u>PART 1 - GENERAL</u>			<u>Number of affirmative replies</u>
1.1	<u>Company Structure</u>		
	a) International	YES/NO*	14
	b) National	YES/NO*	21
	c) National - Structured into regions	YES/NO*	22
	d) Local	YES/NO*	20
	e) Others - Please specify <sup>‡</sup>	YES/NO*	5
1.2	<u>Main Activities</u>		
	a) Housing	YES/NO*	19
	b) Industrial building	YES/NO*	32
	c) Commercial Building	YES/NO*	31
	d) Heavy Civil Engineering Structures	YES/NO*	17
	e) Design/Construct packages	YES/NO*	28
	f) Others - please specify <sup>‡</sup>	YES/NO*	10
1.3	Company Turnover	£.....	
1.4	Number of employees	.....	
<u>PART 2 - PLANNING</u>			
2.1	Does the Company prepare a formal programme, showing the sequence, inter-relationship and duration of the individual activities that constitute a construction project.	YES/NO*	35
2.2	If yes, which of the following techniques is used: -		
	a) Bar charts	YES/NO*	32
	b) CPM	YES/NO*	16
	c) PERT	YES/NO*	6
	d) Other - Please specify <sup>‡</sup>	YES/NO*	5
2.3	If the answer to 2.2b above is yes, is CPM used for: -		
	a) Pretender planning	YES/NO*	5
	b) Post contract planning	YES/NO*	16
	c) Short term planning	YES/NO*	5
2.4	If the answer to 2.2c above is yes, is PERT used for:		
	a) Pretender planning	YES/NO*	4
	b) Post contract planning	YES/NO*	6
	c) Short term planning	YES/NO*	5
<u>PART 3 - COST ANALYSIS/CONTROL</u>			
3.1	Does the Company operate a cost analysis/control system	YES/NO*	3
3.2	If yes to 3.1 above, is the system based on: -		
	a) Bill of quantities (standard method)	YES/NO*	27
	b) Elemental Bill of quantities	YES/NO*	7
	c) Work Measurement	YES/NO*	18
	d) Other - Please specify <sup>‡</sup>	YES/NO*	4

\* Delete as appropriate

‡ Use Sheet 3 if appropriate

#### PART 4 - TIME/COST RELATIONSHIPS

- 4.1 Does the company operate: -
- |  |         |    |
|--|---------|----|
| a) A formal system for relating time/cost      | YES/NO* | 14 |
| b) If yes, is the system based on: -           |         |    |
| i) Manual methods                              | YES/NO* | 10 |
| ii) Main frame computer owned by company       | YES/NO* | 6  |
| iii) Main frame computer - hired time          | YES/NO* | -- |
| iv) Mini computer                              | YES/NO* | -- |
| v) Microcomputer up to 32K owned<br>by company | YES/NO* | -- |
- 4.2 If yes to 4.1a above, is the system based on:
- |  |         |   |
|--|---------|---|
| a) PERT                                | YES/NO* | 1 |
| b) CPM or other network based system   | YES/NO* | 1 |
| c) Other - please specify <sup>‡</sup> | YES/NO* | 2 |
- 4.3 If no, to 4.1a above, are the reasons for not doing so: -
- |   |         |   |
|---|---------|---|
| a) Not considered necessary               | YES/NO* | 4 |
| b) Cost involved; -                       |         |   |
| i) Staff time                             | YES/NO* | 6 |
| ii) Computer time                         | YES/NO* | 5 |
| c) Lack of suitable computer software     | YES/NO* | 8 |
| d) Lack of suitable computer hardware     | YES/NO* | 4 |
| e) Resistance to a time/cost system by: - |         |   |
| Estimators                                | YES/NO* | 2 |
| Planners                                  | YES/NO* | 2 |
| Contract managers                         | YES/NO* | 3 |
| Site management                           | YES/NO* | 3 |
| Others - please specify <sup>‡</sup>      | YES/NO* |   |

#### PART 5 - COMPUTER PACKAGE

- 5.1 Would the Company be interested in: -
- |   |         |    |
|---|---------|----|
| a) Discussing a micro-computer based<br>time/cost package | YES/NO* | 10 |
| b) Testing a microcomputer based<br>time/cost package     | YES/NO* | 8  |
- 5.2 If yes, please contact the undersigned.

Please complete and return this questionnaire to the address shown  
overleaf on or before FRIDAY 6 FEBRUARY 1981.

Where full information is not available, partially completed  
questionnaires would still be helpful.

TOTAL NUMBER OF COMPANIES CIRCULATED - 100  
TOTAL NUMBER OF REPLIES RECEIVED - 40

\* Delete as appropriate  
‡ Use Sheet 3 if necessary



Dimensions:

16½" wide by 18½" deep, 14" overall height, weight, 44lbs

Memory

Random Access Memory 8K

16K and 32K as per model number. Expandable to 32K bytes.

Read Only Memory (operating system resident in the computer)

13K bytes

8K BASIC interpreter

5K operating system

1K machine code monitor

Video Display Monitor

9" enclosed black and green, high resolution CRT

1000 character display, arranged 40 columns by 25 lines

8 x 8 dot matrix for characters and continuous graphics

Automatic scrolling from bottom of screen

Winking cursor with full motion control.

Reverse field on all characters

Keyboard

73 keys.

All 64 ASCII characters available without shift. Calculator style numeric keypad.

All 64 graphic and reverse field characters accessible from keyboard (with shift)

Screen Control

Home and Clear

Editing

Character insertion and deletion

Operating System

Powerful and cursor oriented screen editor. Machine language accessibility

File management in operating system. Cursor control, reverse field and graphics

under simple BASIC control. Real time clock can be accessed from BASIC. File

management in operating system can be handled by BASIC or from machine code.

Input/Output

All other I/O supported through IEEE-488 instrument interface which allows for multiple intelligent peripherals. All I/O automatically managed by operating system software. Single character I/O with GET command. Easy screen line-edit capability allows for BASIC expansion with up to 12 intelligent peripherals.

Direct sensing of key press available.

BASIC Interpreter

Expanded 8K BASIC

Upward expansion from current popular BASIC

Strings, integers and multiple dimension arrays.

10 significant digits, floating point numbers.

Memory access through PEEK and POKE commands.

Machine code subroutines can be called up from BASIC with SYS and USR.

Pseudo random number generator.

Microcomputer system devices: -

## Controller

6504 Microprocessor

6530 I/O RAM, and 1K ROM software

6316 2K ROM for encoding and decoding disk data

6522 I/O and interval timers

## File interface

6502 microprocessor

(2) 6532 RAM I/O interval timers

(2) 6332 4K ROM each (total 8K disk operating system). Shared RAM

Disk Drives:(2) Shugart Associates SA390 drives standard minifloppy (5 $\frac{1}{4}$  disk)

Activity LEDs light when a file is open on that drive

Error LED indicates command or data error.

Packaging

18 gauge all steel cabinet

Dimensions

14.35", height 6.5"

Cover hinges from base for servicing.

Weight: 28lbs

Diskette Organisation

Formatting is by the drive itself - any mini floppy diskette may be used.

35 concentric tracks

Constant density recording on each track varying number of sectors per track.

176640 bytes on a single side.

Track 18 used for directory.

171520 bytes for user storage.

Self

Data Interface

IEEE-488

Standard 24 pin stacking connector.

Device 8-15 by jumper option. Full listener-talker recognizes secondary addressing

Floppy Disk Commands (Summary)

LOAD program

SAVE program

VERIFY program

OPEN datafile (upto 5)

PRINT to data file

CLOSE data file

VALIDATA disk

DUPLICATE disk

COPY program or data file (allows data files to be concatenated)

RENAME disk

SCRATCH unwanted file examine ERROR CHANNEL

Advanced Disk Commands (Summary)

BLOCK-READ

BLOCK-WRITE

BLOCK-EXECUTE

BLOCK-POINTER

BLOCK-ALLOCATE

BLOCK-FREE

Memory Write

Memory read

Memory execute

USER

Microcomputer System devices

6504 Microprocessor  
6532 I/O RAM interval timer (2)  
6332 4K and 8 ROM

Printer Mechanism

Tractor Feed  
Epson DH 70 print Head  
Dot Matrix - 7 x 6, 80 columns per line  
Impact print - original plus 3 copies  
Print rate is 75 LPM (93 CPS)  
Programmable line spacing  
Forms: 8.5 + .5 + x 2 (sprocket margins)  
Pin to pin distance: .5 = longitudinally, 9.0 + laterally  
5/32 = diameter.

Packaging

18 gauge all steel cabinet. Dimensions, width 17", depth 18", height 6½".  
Forms enter from rear or bottom of cabinet. Weight 18lbs.

Data Interface

IEEE-488

Standard 24 pin stacking connector Device 4-11 by jumper option. Listener only. Recognize secondary addressing.

Character Set

Upper Case ASCII  
Lower Case ASCII  
PET graphics.

Control Characters

Enhance printing (doubles size)  
Enable automatic line count and paging  
Page eject  
Print reverse field  
Overprint a line  
Switch to lower case character set  
Print programmable character IEEE secondary address commands.  
Print data exactly as received.  
Accept characters as a format  
Edit data to format  
Alter number of lines per page  
Enable diagnostic messages to print  
Accept data for programmable character.  
Alter paper advance per line feed.

Data Formatting Capability

Field width and decimal position specified  
Leading or trailing sign  
Fixed or floating dollar sign  
Forced leading zeros  
Literal characters always printed  
Alpha fields left justified,

Diagnostic Messages

Can be turned on when desired  
Print on paper  
Describe problems with format and data.

```

10 PRINT "[CLR][CUD]THIS PROGRAM WILL ACCEPT DATA FOR 10
0[CUD]"
20 PRINT "ACTIVITIES WITH A MAXIMUM OF 9[CUD]"
30 PRINT "PRECEDENTS FOR EACH ACTIVITY[CUD][CUD][CUD]"
40 PRINT "AFTER TYPING EACH NUMBER REQUESTED,      PRESS
THE RETURN KEY[CUD][CUD][CUD]"
50 PRINT "TYPE DATA FILE NAMES[CUD]"
60 INPUT "[CUD][CUD]NUMBER      *[CUL][CUL][CUL]";F1$:IF F
1$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 60
70 INPUT "[CUD][CUD]A$MATRIX      *[CUL][CUL][CUL]";FD$:IF
FD$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 70
80 INPUT "[CUD][CUD]AMATRIX      *[CUL][CUL][CUL]";FA$:IF
FA$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 80
90 INPUT "[CUD][CUD]PMATRIX      *[CUL][CUL][CUL]";FP$:IF
FP$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 90
100 INPUT "[CLR][CUD]HOW MANY ACTIVITIES .....  *[CUL]
[CUL][CUL]";B$
110 IF B$="" THEN PRINT "[CUU][CUU]":GOTO 100
120 Z1=VAL(B$):GOSUB 310:IF Q$="Y" OR Z1>100 OR Z1<=0 OR
Z1<>INT(Z1) THEN 10
130 DIM A$(100)
140 PRINT "[CLR][CUD]CONTRACT DESCRIPTION[CUD][CUD]":INPUT
"      *[CUL][CUL][CUL]";A$(0)
150 IF A$(0)="" THEN 140
160 GOSUB 310:IF Q$="Y" THEN 140
170 GOSUB 370:DIM A(100,20):GOSUB 390
180 PRINT "[CLR][CUD]INDIRECT COSTS PER TIME UNIT[CUD][CUD]
":INPUT "      *[CUL][CUL][CUL]";B$
190 IF B$="" THEN 180
200 A(1,12)=VAL(B$):GOSUB 310:IF Q$="Y" THEN 180
210 DIM PJ(10,50):GOSUB 1270
220 IF E=1 THEN GOSUB 1250
230 GOSUB 1770
240 PRINT "[CLR][CUD][CUD][CUD]                WRITING DATA TO
DISK"
250 PRINT "[CUD]                WAIT FOR END OF RUN MESSAGE":GOSUB
980:GOSUB 1010
260 IF E<>1 THEN GOSUB 1220
270 PRINT "[CUD][CUD]DO YOU REQUIRE A LISTING OF YOUR INP
UT ON THE PRINTER ?"
280 GOSUB 320:IF Q$= "N" THEN 300
290 GOSUB 1030:GOSUB 1080:GOSUB 1160:GOSUB 1660
300 PRINT "[CLR][CUD]END OF RUN":END
310 PRINT "[CUD][CUD]DO YOU WISH TO MAKE ANY CHANGES ?"
320 PRINT "[CUD]TYPE Y FOR YES OR N FOR NO[CUD]"
330 FOR Q1=1 TO 10:GET Q$:NEXT
340 GET Q$:IF Q$="" THEN 340
350 IF Q$="Y" OR Q$="N" THEN RETURN
360 GOTO 340
370 OPEN 1,8,15:OPEN 2,8,2,"@0: "+F1$+"",S,W":GOSUB 1840:PRINT#
2,Z1;CHR$(13);
380 GOSUB 1840:CLOSE 2:CLOSE 1:RETURN
390 REM *****
400 REM *****  THIS SUBROUTINE REQUESTS INPUT DATA FOR EA
CH ACTIVITY *****
410 REM *****

```

```

830 PRINT "[CLR][CUD]HOW MANY PRECEDENTS FOR ACTIVITY";J;
:INPUT " *[CUL][CUL][CUL]";B$
840 IF B$="" THEN 830
850 Z2=VAL(B$):PRINT:IF Z2<0 OR Z2>9 OR Z2<>INT(Z2) THEN
830
860 IF Z2=0 THEN 940
870 PRINT "INPUT PRECEDENTS IN ASCENDING ORDER":PRINT
880 FOR K=3 TO Z2+2
890 PRINT "PRECEDENT";K-2;:INPUT " *[CUL][CUL][CUL]";B$
900 IF B$="" THEN PRINT "[CUU][CUU]":GOTO 890
910 A(J,K)=VAL(B$):IF K=3 THEN 930
920 IF A(J,K)<A(J,K-1) THEN PRINT "[CUD]*** INCORRECT PR
ECEDENT ***[CUD]":GOTO 870
930 NEXT
940 GOSUB 310:IF Q$="Y" THEN 830
950 IF Z2=0 THEN A(J,3)=999:GOTO 970
960 IF Z2<>9 THEN A(J,K)=999
970 NEXT:RETURN
980 OPEN 1,8,15:OPEN 2,8,2,"@:"+FA$+",S,W":GOSUB 1840:FOR
J=0 TO 20
990 FOR I=0 TO Z1:PRINT#2,A(I,J);CHR$(13);:GOSUB 1840:NEXT
I,J:CLOSE 2:CLOSE 1
1000 RETURN
1010 OPEN 1,8,15:OPEN 2,8,2,"@:"+FD$+",S,W":GOSUB 1840:FOR
I=0 TO Z1
1020 PRINT#2,A$(I);CHR$(13);:GOSUB 1840:NEXT:CLOSE 2:CLOSE
1:RETURN
1030 OPEN 1,8,15:OPEN 2,8,2,"0:"+F1$+",S,R":GOSUB 1840:INPUT#
2,Z1:GOSUB 1860
1040 OPEN 1,4:PRINT#1,CHR$(147)
1050 PRINT#1,TAB(21);"DATA WRITTEN TO DISK FROM INCRIT PRO
GRAM"
1060 PRINT#1,TAB(21);:FOR I=1 TO 40:PRINT#1," ";:NEXT:PRINT#
1
1070 PRINT#1:PRINT#1," NUMBER OF ACTIVITIES";Z1:PRINT#1:PRINT#
1:CLOSE 1:RETURN
1080 OPEN 1,8,15:OPEN 2,8,2,"0:"+FD$+",S,R":GOSUB 1840:FOR
I=0 TO Z1
1090 INPUT#2,A$(I):GOSUB 1860:NEXT
1100 OPEN 1,4:PRINT#1," CONTRACT DESCRIPTION":PRINT#1," —
"
1110 PRINT#1:PRINT#1,TAB(1);A$(0):PRINT#1
1120 PRINT#1:PRINT#1," ACTIVITY"," ACTIVITY":PRINT#1,"
NUMBER",
1130 PRINT#1," DESCRIPTION":PRINT#1:PRINT#1:C8=0:FOR
I=1 TO Z1
1140 PRINT#1,I;TAB(22-LEN(STR$(I)));A$(I):C8=C8+1:IF C8=5
THEN C8=0:PRINT#1
1150 NEXT:PRINT#1:CLOSE 1:RETURN
1160 OPEN 1,8,15:OPEN 2,8,2,"0:"+FA$+",S,R":GOSUB 1840:FOR
J=0 TO 20
1170 FOR I=0 TO Z1:INPUT#2,A(I,J):GOSUB 1860:NEXT I,J:OPEN
1,4:PRINT#1:PRINT#1
1180 PRINT#1," NUMERIC DATA REFERENCE NUMBER";A(0,0):PRINT#
1:PRINT#1

```

```

1190 FOR I=1 TO Z1:A(I,20)=INT(A(I,20)*100+.5)/100:FOR J=1
    TO 5:FOR Q=0 TO 3
1200 PRINT#1,J+Q*5;"-";A(I,J+Q*5);TAB(17-LEN(STR$(J+Q*5))+STR$
    (A(I,J+Q*5)))
1210 NEXT:PRINT#1:NEXT:PRINT#1:PRINT#1:NEXT:CLOSE 1:RETURN

1220 OPEN 1,8,15:OPEN 2,8,2,"@0:"+FP$+",S,W":GOSUB 1840:FOR
    I=0 TO 10
1230 FOR J=0 TO 50:PRINT#2,PJ(I,J);CHR$(13);:GOSUB 1840:NEXT
    J,I:CLOSE 2
1240 CLOSE 1:RETURN
1250 OPEN 1,8,15:OPEN 2,8,2,"0:"+FP$+",S,R":GOSUB 1840:FOR
    I=0 TO 10
1260 FOR J=0 TO 50:INPUT#2,PJ(I,J):GOSUB 1860:NEXT J,I:RETURN

1270 REM ***** DETAILED COSTING INPUT DATA *****
1280 E=0:INPUT "DETAILED COSTING REFERENCE NUMBER    *[CUL]
    [CUL][CUL]";B$
1290 IF B$="" THEN PRINT "[CUU][CUU]":GOTO 1280
1300 PJ(0,0)=VAL(B$):GOSUB 310:IF Q$="Y" THEN 1280
1310 PRINT "TYPE THE ACTIVITY NUMBER OF THE ACTIVITY"
1320 PRINT "FOR WHICH YOU REQUIRE DETAILED COSTING":PRINT
    "(0 TO END)[CUD]"
1330 INPUT "    *[CUL][CUL][CUL]";B$:IF B$="" THEN PRINT "[CUU]
    [CUU]":GOTO 1330
1340 I=VAL(B$):PRINT "[CUD][CUD]":IF I<0 OR I>100 OR I<>INT
    (I) THEN 1310
1350 IF I=0 THEN RETURN
1360 P=999:FOR K=1 TO 10:IF PJ(K,1)=I THEN P=K
1370 NEXT:IF P>10 THEN 1470
1380 PRINT "[CLR][CUD]EXISTING DATA FOR ACTIVITY";I;"[CUD]
    ":GOSUB 1620
1390 PRINT "[CUD][CUD]TYPE NUMBER OF DATA ITEM THAT IS TO
    BE[CUD]"
1400 INPUT "ALTERED    *[CUL][CUL][CUL]";B$:IF B$="" THEN
    PRINT "[CUU][CUU]":GOTO 1400
1410 J=VAL(B$):IF J<1 OR J>50 OR J<>INT(J) THEN 1390
1420 PRINT "[CUD][CUD]TYPE NEW DATA FOR ACTIVITY";I;:PRINT
    "ITEM";J:PRINT
1430 INPUT "    *[CUL][CUL][CUL]";B$:IF B$="" THEN PRINT "[CUU]
    [CUU]":GOTO 1430
1440 PJ(P,J)=VAL(B$)
1450 PRINT "[CUD][CUD]ANY MORE ALTERATIONS ?":GOSUB 320:IF
    Q$="Y" THEN 1380
1460 PRINT "[CLR][CUD]AMENDED DATA FOR ACTIVITY";I;"[CUD]"
    :- 1620:) 1310
1470 FOR K=1 TO 10:IF PJ(K,1)=0 THEN P=K
1480 NEXT:IF P<11 THEN 1500
1490 PRINT "[CUD]NO SPACE FOR MORE DATA":GOTO 1530
1500 PJ(P,1)=I:T=A(I,18):MD=A(I,2):S=T-1:PRINT "[CUD]CRASH
    DURATION IS";T
1510 PRINT "[CUD]MINIMUM COST DURATION IS";MD:IF MD<T+51 THEN
    1540
1520 PRINT "[CUD]MORE THAN 49 INTERMEDIATE POINTS"
1530 E=1:PRINT "[CUD]PMATRIX WILL NOT BE AMENDED[CUD]":RETURN

```

```

1540 FOR D=2 TO 50:T=S+D
1550 IF T>=MD THEN PRINT "[CUD]COSTS DEFINED AT ALL POINTS
      [CUD]":D=50:GOTO 1590
1560 PRINT "[CUD]FOR DURATION";T
1570 INPUT "[CUD]WHAT IS THE COST  * [CUL][CUL][CUL]";B$:IF
      B$="" THEN PRINT "[CUU][CUU][CUU]":GOTO 1570
1580 PJ(P,D)=VAL(B$)
1590 NEXT:PRINT "YOU HAVE JUST TYPED FOR ACTIVITY";I;"[CUD]
      ":GOSUB 1620:GOSUB 310
1600 IF Q$="Y" THEN 1390
1610 GOTO 1310
1620 FOR J=1 TO 16:FOR Q=0 TO 2
1630 PRINT TAB(13*Q);J+Q*17;"-";PJ(P,J+Q*17);:NEXT:PRINT:NEXT

1640 J=17:FOR Q=0 TO 1
1650 PRINT TAB(13*Q);J+Q*17;"-";PJ(P,J+Q*17);:NEXT:PRINT:RETURN

1660 GOSUB 1250:OPEN 1,4:PRINT#1:PRINT#1
1670 PRINT#1," DETAILED COSTING REFERENCE NUMBER";PJ(0,0):
      PRINT#1:PRINT#1
1680 C7=0:FOR I=1 TO 10:C8=0:IF PJ(I,1)=0 THEN C7=C7+1:GOTO
      1750
1690 FOR J=1 TO 11:FOR Q=0 TO 3:PRINT#1,J+Q*13;"-";PJ(I,J+
      Q*13);
1700 PRINT#1,TAB(17-LEN(STR$(J+Q*13)+STR$(PJ(I,J+Q*13)))));
      :NEXT:PRINT#1
1710 C8=C8+1:IF C8=5 THEN C8=0:PRINT#1
1720 NEXT:FOR J=12 TO 13:FOR Q=0 TO 2:PRINT#1,J+Q*13;"-";P
      J(I,J+Q*13);
1730 PRINT#1,TAB(17-LEN(STR$(J+Q*13)+STR$(PJ(I,J+Q*13)))));
      :NEXT:PRINT#1:NEXT
1740 PRINT#1:PRINT#1
1750 NEXT:IF C7=10 THEN PRINT#1," NO DETAILED COSTING EXIS
      TS"
1760 PRINT#1,CHR$(19):CLOSE 1:RETURN
1770 FOR IJ=1 TO 21:IF A(IJ,2)<=A(IJ,18) THEN A(IJ,20)=0:GOTO
      1810
1780 N=18:IF A(IJ,2)>A(IJ,13) AND A(IJ,13)>=A(IJ,18) THEN
      N=13
1790 IF A(IJ,2)>A(IJ,15) AND A(IJ,15)>=A(IJ,18) THEN N=15
1800 A(IJ,20)=(A(IJ,N+1)-A(IJ,17))/(A(IJ,2)-A(IJ,N))
1810 NEXT:FOR K=1 TO 10:J=PJ(K,1)
1820 IF J>=1 THEN N=A(J,2)-A(J,18):A(J,20)=PJ(K,N)-A(J,17)

1830 NEXT:RETURN
1840 INPUT#1,EN$,EM$,ET$,ES$:IF EN$="00" THEN RETURN
1850 PRINT "[CUD][CUD][CUD][REV]ERROR ON DISK[OFF][CUD][CUD]
      [CUD]":PRINT EM$,EN$,ET$,ES$:CLOSE 2:CLOSE 1:END
1860 RS=ST:GOSUB 1840:IF RS=0 THEN RETURN
1870 IF RS=64 THEN CLOSE 2:CLOSE 1:RETURN
1880 PRINT "[CUD][CUD][CUD][REV]BAD DISK[OFF] STATUS IS"
      ;RS:CLOSE 2:CLOSE 1:END

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```

10 PRINT "[CLR]THIS PROGRAM WILL ALTER SELECTED DATA"
20 PRINT "FROM THAT WHICH IS ALREADY HELD ON DISK"
30 PRINT "FOR THE CRITICAL PATH ANALYSIS PROGRAM[CUD]"
40 PRINT "AFTER TYPING EACH NUMBER REQUESTED,      PRESS
    THE RETURN KEY[CUD]"
50 PRINT "[CUD][CUD]TYPE DATA FILE NAMES[CUD]"
60 INPUT "[CUD][CUD]NUMBER      *[CUL][CUL][CUL]";F1$:IF F
    1$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 60
70 INPUT "[CUD][CUD]A$MATRIX      *[CUL][CUL][CUL]";FD$:IF
    FD$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 70
80 INPUT "[CUD][CUD]AMATRIX      *[CUL][CUL][CUL]";FA$:IF
    FA$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 80
90 INPUT "[CUD][CUD]PMATRIX      *[CUL][CUL][CUL]";FP$:IF
    FP$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 90
100 GOSUB 470:DIM A(100,20),A$(100),PJ(10,50)
110 PRINT "[CUD][CUD]DO YOU WISH TO ALTER ANY OF THE DATA
    ?":GOSUB 490
120 IF Q$="N" THEN 440
130 PRINT "NUMBER OF ACTIVITIES HELD IS";Z1
140 PRINT "[CUD][CUD][CUD][REV]WAIT[OFF]      READING DATA F
    ROM DISK"
150 GOSUB 570:GOSUB 590:GOSUB 610:GOSUB 630
160 GOSUB 1920
170 PRINT "[CUD][CUD]TYPE      D TO ALTER NUMERIC DATA"
180 PRINT "      OR I TO ALTER INDIRECT COSTS"
190 PRINT "      OR N TO ALTER ACTIVITY DESCRIPTION"
200 PRINT "      OR C TO ALTER DETAILED COSTING[CUD][CUD]
    "
210 INPUT "      *[CUL][CUL][CUL]";T$:IF T$="" THEN PRINT "[CUU]
    [CUU]":GOTO 210
220 IF T$="I" THEN M=4:GOTO 310
230 IF T$<>"D" AND T$<>"N" AND T$<>"C" THEN 170
240 PRINT "[CLR][CUD][CUD]TYPE THE ACTIVITY NUMBER OF THE
    ACTIVITY"
250 PRINT "THAT YOU WISH TO ALTER[CUD][CUD]"
260 INPUT "      *[CUL][CUL][CUL]";B$:IF B$="" THEN PRINT "[CUU]
    [CUU]":GOTO 260
270 I=VAL(B$):IF I<0 OR I>100 OR I<>INT(I) THEN 240
280 IF T$="D" THEN M=1:GOTO 310
290 IF T$="N" THEN M=2:GOTO 310
300 IF T$="C" THEN M=3:GOTO 310
310 ON M GOSUB 660,1390,1000,1590
320 GOSUB 1350
330 PRINT "[CLR][CUD][CUD]ANY MORE ALTERATIONS TO ACTIVIT
    IES ?":GOSUB 490
340 IF Q$="Y" THEN 170
350 IF E=1 THEN GOSUB 610
360 GOSUB 1920
370 PRINT "[CUD][CUD]TYPE NEW DATA FILE NAMES[CUD]"
380 INPUT "[CUD][CUD]NUMBER      *[CUL][CUL][CUL]";F1$:IF F
    1$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 380
390 INPUT "[CUD][CUD]A$MATRIX      *[CUL][CUL][CUL]";FD$:IF
    FD$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 390
400 INPUT "[CUD][CUD]AMATRIX      *[CUL][CUL][CUL]";FA$:IF
    FA$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 400
410 IF E=1 THEN 430

```



```

770 INPUT " *[CUL][CUL][CUL]";B$:IF B$="*" THEN PRINT "[CUU]
[CUU]":GOTO 770
780 A(I,J)=VAL(B$):IF A(I,18)>A(I,2) OR A(I,17)>A(I,19) THEN
880
790 IF A(I,13)=0 THEN 830
800 IF A(I,15)=0 AND (A(I,18)>A(I,13) OR A(I,13)>A(I,2))
THEN 880
810 IF A(I,15)=0 THEN 830
820 IF A(I,18)>A(I,13) OR A(I,13)>A(I,15) OR A(I,15)>A(I,
2) THEN 880
830 IF A(I,14)=0 THEN 910
840 IF A(I,16)=0 AND (A(I,17)>A(I,14) OR A(I,14)>A(I,19))
THEN 880
850 IF A(I,16)=0 THEN 910
860 IF A(I,17)>A(I,16) OR A(I,16)>A(I,14) OR A(I,14)>A(I,
19) THEN 880
870 GOTO 910
880 PRINT "[CUD][CUD][REV]ERROR[OFF] DO YOU WISH TO TRY A
GAIN ?":GOSUB 490
890 IF Q$="N" THEN 440
900 PRINT "INVALID AMENDED DATA FOR ACTIVITY";I:PRINT:GOSUB
1530:GOTO 730
910 FOR K=3 TO 11:IF A(I,K)=999 THEN 970
920 IF K=3 THEN 960
930 IF A(I,K)>=A(I,K-1) THEN 960
940 PRINT "[CUD]*** INCORRECT PRECEDENT ***[CUD]"
950 PRINT "INVALID AMENDED DATA FOR ACTIVITY";I:PRINT:GOSUB
1530:K=11:M1=1
960 NEXT:IF M1=1 THEN 730
970 PRINT "[CUD][CUD]ANY MORE ALTERATIONS ?":GOSUB 490:IF
Q$="Y" THEN 720
980 PRINT "[CLR][CUD]AMENDED DATA FOR ACTIVITY";I:PRINT:GOSUB
1530
990 RETURN
1000 PRINT "[CLR][CUD]EXISTING DETAILED COSTING REFERENCE[CUD]
":PRINT "NUMBER";PJ(0,0)
1010 E=0:PRINT:PRINT:GOSUB 1380:IF Q$="N" THEN 1050
1020 PRINT "TYPE DETAILED COSTING REFERENCE NUMBER[CUD]"
1030 INPUT " *[CUL][CUL][CUL]";B$:IF B$="*" THEN PRINT "[CUU]
[CUU]":GOTO 1030
1040 PJ(0,0)=VAL(B$):PRINT:GOSUB 1380:IF Q$="Y" THEN 1020
1050 IF I=0 THEN RETURN
1060 P=999:FOR K=1 TO 10:IF PJ(K,1)=I THEN P=K
1070 NEXT:IF P>10 THEN 1170
1080 PRINT "[CLR][CUD]EXISTING DATA FOR ACTIVITY";I:PRINT:
GOSUB 1550
1090 PRINT "[CUD][CUD]TYPE NUMBER OF DATA ITEM THAT IS TO
BE[CUD]"
1100 INPUT "ALTERED *[CUL][CUL][CUL]";B$:IF B$="*" THEN
PRINT "[CUU][CUU]";GOTO 1100
1110 J=VAL(B$):IF J<1 OR J>50 OR J<>INT(J) THEN 1090
1120 PRINT "[CUD][CUD]TYPE NEW DATA FOR ACTIVITY";I:PRINT
"ITEM";J:PRINT
1130 INPUT " *[CUL][CUL][CUL]";B$:IF B$="*" THEN PRINT "[CUU]
[CUU]":GOTO 1130
1140 PJ(P,J)=VAL(B$)

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1150 PRINT "[CUD][CUD]ANY MORE ALTERATIONS ?":GOSUB 490:IF
    Q$="Y" THEN 1080
1160 PRINT "[CLR][CUD]AMENDED DATA FOR ACTIVITY";I:PRINT:GOSUB
    1550:RETURN
1170 FOR K=1 TO 10:IF PJ(K,1)=0 THEN P=K
1180 NEXT:IF P<11 THEN 1200
1190 PRINT "[CUD]NO SPACE FOR MORE DATA":GOTO 1230
1200 PJ(P,1)=I:T=A(I,18):MD=A(I,2):S=T-1:PRINT "[CUD]CRASH
    DURATION IS";T
1210 PRINT "[CUD]MINIMUM COST DURATION IS";MD:IF MD<T+51 THEN
    1240
1220 PRINT "[CUD]MORE THAN 49 INTERMEDIATE POINTS"
1230 E=1:PRINT "[CUD]PMATRIX WILL NOT BE AMENDED[CUD]":RETURN

1240 FOR D=2 TO 50:T=S+D
1250 IF T>=MD THEN PRINT "[CUD]COSTS DEFINED AT ALL POINTS
    [CUD]":D=50:GOTO 1290
1260 PRINT "[CUD]FOR DURATION";T:PRINT
1270 INPUT "WHAT IS THE COST *[CUL][CUL][CUL]";B$:IF B$=
    "*" THEN PRINT "[CUU][CUU]":GOTO 1270
1280 PJ(P,D)=VAL(B$)
1290 NEXT:PRINT "YOU HAVE JUST TYPED FOR ACTIVITY";I:PRINT
    :GOSUB 1550:RETURN
1300 OPEN 1,8,15:OPEN 2,8,2,"@0:"+FA$+",S,W":GOSUB 1990:FOR
    J=0 TO 20
1310 FOR I=0 TO Z1:PRINT#2,A(I,J);CHR$(13);:GOSUB 1990:NEXT
    I,J:CLOSE 2
1320 CLOSE 1:RETURN
1330 OPEN 1,8,15:OPEN 2,8,2,"@0:"+FD$+",S,W":GOSUB 1990:FOR
    I=0 TO Z1
1340 PRINT#2,A$(I);CHR$(13);:GOSUB 1990:NEXT:CLOSE 2:CLOSE
    1:RETURN
1350 PRINT "[CUD][CUD][CUD][REV]PRESS[OFF] ANY KEY TO CONT
    INUE":FOR X7=1 TO 10:GET Z9$:NEXT
1360 GET Z9$:IF Z9$="" THEN 1360
1370 RETURN
1380 PRINT "[CUD][CUD]DO YOU WISH TO CHANGE THIS ?":GOSUB
    490:RETURN
1390 PRINT "[CLR][CUD]EXISTING CONTRACT DESCRIPTION[CUD]":
    PRINT A$(0):PRINT:PRINT
1400 GOSUB 1380:IF Q$="N" THEN 1440
1410 PRINT "TYPE NEW CONTRACT DESCRIPTION[CUD]"
1420 INPUT " *[CUL][CUL][CUL]";A$(0):IF A$(0)="*" THEN PRINT
    "[CUU][CUU]":GOTO 1420
1430 PRINT:GOSUB 1380:IF Q$="Y" THEN 1410
1440 IF I=0 THEN RETURN
1450 PRINT "[CLR][CUD][CUD]EXISTING ACTIVITY DESCRIPTION F
    OR[CUD]":PRINT "ACTIVITY";I
1460 PRINT:PRINT A$(I)
1470 PRINT "[CUD][CUD]TYPE NEW ACTIVITY DESCRIPTION FOR[CUD]
    ":PRINT "ACTIVITY";I:PRINT
1480 INPUT " *[CUL][CUL][CUL]";A$(I):IF A$(I)="*" THEN PRINT
    "[CUU][CUU]":GOTO 1480
1490 GOSUB 1380:IF Q$="Y" THEN 1450
1500 RETURN

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1510 PRINT "[CLR][CUD][CUD][CUD]                WRITING DATA TO
        DISK"
1520 PRINT "[CUD]                WAIT FOR END OF RUN MESSAGE":RETURN

1530 FOR J=1 TO 10:FOR Q=0 TO 1
1540 PRINT TAB(20*Q);J+Q*10;"-";A(I,J+Q*10);:NEXT:PRINT:NEXT
        :PRINT:PRINT:RETURN
1550 FOR J=1 TO 16:FOR Q=0 TO 2
1560 PRINT TAB(13*Q);J+Q*17;"-";PJ(P,J+Q*17);:NEXT:PRINT:NEXT

1570 J=17:FOR Q=0 TO 1
1580 PRINT TAB(13*Q);J+Q*17;"-";PJ(P,J+Q*17);:NEXT:PRINT:RETURN

1590 PRINT "[CUD][CUD][CUD]EXISTING INDIRECT COSTS";A(1,12
        ):PRINT
1600 INPUT "TYPE NEW INDIRECT COSTS    *[CUL][CUL][CUL]";B$

1610 IF B$="*" THEN PRINT "[CUU][CUU]":GOTO 1600
1620 A(1,12)=VAL(B$):GOSUB 1380:IF Q$="Y" THEN 1590
1630 I=0:GOSUB 660:RETURN
1640 GOSUB 470:OPEN 1,4:PRINT#1,CHR$(147)
1650 PRINT#1,TAB(21);"DATA WRITTEN TO DISK FROM AMCRIT PRO
        GRAM"
1660 PRINT#1,TAB(21);:FOR I=1 TO 40:PRINT#1," ";:NEXT:PRINT#
        1:PRINT#1
1670 PRINT#1," NUMBER OF ACTIVITIES";Z1:PRINT#1:PRINT#1:CLOSE
        1:RETURN
1680 GOSUB 590:OPEN 1,4:PRINT#1," CONTRACT DESCRIPTION"
1690 PRINT#1," _____":PRINT#1:PRINT#1,TAB(1
        );A$(0):PRINT#1
1700 PRINT#1:PRINT#1," ACTIVITY", " ACTIVITY"
1710 PRINT#1," NUMBER", " DESCRIPTION":PRINT#1:PRINT#1
        :C8=0:FOR I=1 TO Z1
1720 PRINT#1,I:TAB(22-LEN(STR$(I)));A$(I):C8=C8+1:IF C8=5
        THEN C8=0:PRINT#1
1730 NEXT:PRINT#1:CLOSE 1:RETURN
1740 GOSUB 570:OPEN 1,4:PRINT#1:PRINT#1
1750 PRINT#1," NUMERIC DATA REFERENCE NUMBER";A(0,0):PRINT#
        1:PRINT#1
1760 FOR I=1 TO Z1:A(I,20)=INT(A(I,20)*100+.5)/100:FOR J=1
        TO 5:FOR Q=0 TO 3
1770 PRINT#1,J+Q*5;"-";A(I,J+Q*5);TAB(17-LEN(STR$(J+Q*5)+STR$
        (A(I,J+Q*5))))
1780 NEXT:PRINT#1:NEXT:PRINT#1:PRINT#1:NEXT:CLOSE 1:RETURN

1790 GOSUB 610:OPEN 1,4:PRINT#1:PRINT#1
1800 PRINT#1," DETAILED COSTING REFERENCE NUMBER";PJ(0,0):
        PRINT#1:PRINT#1
1810 C7=0:FOR I=1 TO 10:C8=0:IF PJ(I,1)=0 THEN C7=C7+1:GOTO
        1880
1820 FOR J=1 TO 11:FOR Q=0 TO 3:PRINT#1,J+Q*13;"-";PJ(I,J+
        Q*13);
1830 PRINT#1,TAB(17-LEN(STR$(J+Q*13)+STR$(PJ(I,J+Q*13)))):
        NEXT:PRINT#1
1840 C8=C8+1:IF C8=5 THEN C8=0:PRINT#1

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1850 NEXT:FOR J=12 TO 13:FOR Q=0 TO 2:PRINT#1,J+Q*13;"-";P
      J(I,J+Q*13);
1860 PRINT#1,TAB(17-LEN(STR$(J+Q*13))+STR$(PJ(I,J+Q*13)))):
      NEXT:PRINT#1:NEXT
1870 PRINT#1:PRINT#1
1880 NEXT:IF C7=10 THEN PRINT#1," NO DETAILED COSTING EXIS
      TS"
1890 PRINT#1,CHR$(19):CLOSE 1:RETURN
1900 OPEN 1,8,15:OPEN 2,8,2,"@0:"+F1$+" ,S,W":GOSUB 1990:PRINT#
      2,Z1;CHR$(13);
1910 GOSUB 1990:CLOSE 2:CLOSE 1:RETURN
1920 FOR IJ=1 TO Z1:IF A(IJ,2)<=A(IJ,18) THEN A(IJ,20)=0:GOTO
      1960
1930 N=18:IF A(IJ,2)>A(IJ,13) AND A(IJ,13)>=A(IJ,18) THEN
      N=13
1940 IF A(IJ,2)>A(IJ,15) AND A(IJ,15)>=A(IJ,18) THEN N=15
1950 A(IJ,20)=(A(IJ,N+1)-A(IJ,17))/(A(IJ,2)-A(IJ,N))
1960 NEXT:FOR K=1 TO 10:J=PJ(K,1)
1970 IF J>=1 THEN N=A(J,2)-A(J,18):A(J,20)=PJ(K,N)-A(J,17)

1980 NEXT:RETURN
1990 INPUT#1,EN$,EM$,ET$,ES$:IF EN$="00" THEN RETURN
2000 PRINT "[CUD][CUD][CUD][REV]ERROR ON DISK[OFF][CUD][CUD]
      [CUD]":PRINT EM$,EN$,ET$,ES$:CLOSE 2:CLOSE 1:END
2010 RS=ST:GOSUB 1990:IF RS=0 THEN RETURN
2020 IF RS=64 THEN CLOSE 2:CLOSE 1:RETURN
2030 PRINT "[CUD][CUD][CUD][REV]BAD DISK[OFF]      STATUS IS"
      ;RS:CLOSE 2:CLOSE 1:END

```

```

10 REM ***** CRITICAL PATH FOR CONTRACT TENDERING *****
  *
20 REM *****
30 DIM A(100,20),A$(100),C(100,2),CT(100),DR(100),E(100)
  ,M(100),PJ(10,50)
40 DIM R(100),MN(100):NJ=100:DEF FNA(W)=INT(W*100+.5)/10
  0
50 PRINT "[CLR]TYPE DATA FILE NAMES[CUD][CUD]{CUD}":PRINT
  "AFTER TYPING EACH NAME REQUESTED"
60 PRINT "[CUD]PRESS THE RETURN KEY[CUD]"
70 INPUT "[CUD][CUD]NUMBER      *[CUL][CUL][CUL]";F1$:IF F
  1$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 70
80 INPUT "[CUD][CUD]A$MATRIX      *[CUL][CUL][CUL]";FD$:IF
  FD$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 80
90 INPUT "[CUD][CUD]AMATRIX      *[CUL][CUL][CUL]";FA$:IF
  FA$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 90
100 INPUT "[CUD][CUD]PMATRIX      *[CUL][CUL][CUL]";FP$:IF
  FP$="" THEN PRINT "[CUU][CUU][CUU][CUU]":GOTO 100
110 PRINT "[CUD][CUD][CUD]":GOSUB 2320:IF Z1>0 AND Z1<=NJ
  AND Z1=INT(Z1) THEN 140
120 PRINT "[CLR][CUD][CUD][CUD][REV]ERROR[OFF]":PRINT"[CUD]
  MAXIMUM NUMBER OF ACTIVITIES IS";NJ;"[CUD]"
130 PRINT "THE NUMBER MUST BE A POSITIVE INTEGER[CUD][CUD]
  [CUD]":END
140 PRINT "[CLR][CUD][CUD][CUD]THIS CRITICAL PATH PROGRAM
  WILL HANDLE"
150 PRINT "UP TO";NJ;"DIFFERENT ACTIVITIES"
160 PRINT "[CUD][CUD][CUD]THE PROGRAM IS NOW DEALING WITH
  ";Z1:PRINT "ACTIVITIES"
170 PRINT "[CUD][CUD][CUD]DO YOU REQUIRE OUTPUT ON THE SC
  REEN,"
180 PRINT "OR ON THE PRINTER,"
190 PRINT "OR ON THE PRINTER AND THE SCREEN ?[CUD]"
200 PRINT "TYPE S FOR SCREEN OR P FOR PRINTER":PRINT "  O
  R B FOR BOTH[CUD]"
210 FOR Q1=1 TO 10:GET V9$:NEXT
220 GET V9$:IF V9$="" THEN 220
230 IF V9$<>"S" AND V9$<>"P" AND V9$<>"B" THEN 220
240 PRINT "[CLR][CUD][CUD][CUD]DO YOU REQUIRE DETAILED IN
  FORMATION FOR EACH PROJECT DURATION ?"
250 PRINT "[CUD][CUD]TYPE Y FOR YES OR N FOR NO[CUD][CUD]
  "
260 FOR Q1=1 TO 10:GET F9$:NEXT
270 GET F9$:IF F9$="" THEN 270
280 IF F9$<>"Y" AND F9$<>"N" THEN 270
290 IF F9$="Y" THEN F9=2:GOTO 310
300 F9=1
310 S9=1:C5=0:C6=0:PRINT "[CUD][CUD][CUD]READING DATA FRO
  M DISK"
320 GOSUB 2390:GOSUB 2410:GOSUB 2430:PRINT "[CLR]"
330 GOSUB 340:GOSUB 460:GOSUB 690:GOTO 330
340 PRINT "[CUD][CUD][CUD]      FORWARD SWEEP THROUGH MATR
  IX"
350 C(1,1)=A(1,2):FOR I=2 TO Z1:C(I,1)=0:FOR K=3 TO 11
360 IF A(I,K)=999 OR A(I,K)=0 THEN K=11:GOTO 380
370 J=A(I,K):IF C(I,1)<=C(J,1) THEN C(I,1)=C(J,1)

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820 C=C-A(IJ,20):CT(S9-1)=CT(S9-1)-A(IJ,20):MN(IJ)=MN(IJ)
    +1
830 PRINT "[CUD][CUD][CUD]RELAX ACTIVITY";IJ
840 PRINT "[CUD]COST SAVING";FNA(A(IJ,20))
850 IF V9$<>"S" AND F9=1 THEN GOSUB 1860
860 T=0:S9=S9-1:RETURN
870 IF QT=1 THEN GOSUB 1900
880 GOSUB 890:GOSUB 1480:RETURN
890 REM *****
900 REM ***** OUTPUT *****
910 REM *****
920 IF F6=2 AND F9=2 THEN GOSUB 2120:RETURN
930 IF V9$="S" OR V9$="B" THEN GOSUB 990
940 IF V9$="B" OR V9$="P" THEN GOSUB 1220
950 IF V9$="S" OR V9$="B" THEN GOSUB 1150
960 IF V9$="B" OR V9$="P" THEN GOSUB 1390
970 IF F6=2 THEN GOSUB 2120
980 RETURN
990 REM *****
1000 REM ***** OUTPUT ON SCREEN *****
1010 REM *****
1020 IF F7=1 THEN RETURN
1030 C1=0:FOR J=1 TO Z1:IF C1=0 THEN PRINT "[CLR]"
1040 PRINT "ACTIVITY NUMBER",A(J,1)
1050 PRINT "DURATION",,INT(A(J,2))
1060 PRINT "COST",,FNA(A(J,17))
1070 PRINT "ACTIVITY DESCRIPTION",A$(J)
1080 C1=C1+1:PRINT "[CUD][CUD]"
1090 IF C1=3 THEN C1=0:GOSUB 2220
1100 NEXT:GOSUB 2220
1110 PRINT "[CLR]";TAB(13);"CRITICAL PATH":PRINT TAB(13);"
    "":PRINT

1120 PRINT E(1);:FOR J=2 TO Z1:IF E(J)=0 THEN J=Z1:GOTO 11
    40
1130 PRINT "-";E(J);
1140 NEXT:PRINT "[CUD][CUD][CUD][CUD]":GOSUB 2220:RETURN
1150 IF F7=1 THEN 1210
1160 C2=FNA(C):C3=T*A(1,12):C4=C2+C3
1170 PRINT "[CLR]PROJECT DURATION",,T:PRINT
1180 PRINT "PROJECT COSTS    INDIRECT",C3:PRINT
1190 PRINT "                DIRECT",C2:PRINT
1200 PRINT "                TOTAL",C4:PRINT "[CUD][CUD][CUD]
    ":GOSUB 2220
1210 F7=F9:RETURN
1220 REM *****
1230 REM ***** OUTPUT ON PRINTER *****
1240 REM *****
1250 IF F8=1 THEN RETURN
1260 OPEN 1,4:PRINT#1,CHR$(147):T$="+":GOSUB 1470
1270 PRINT#1,"ACTIVITY    DURATION    COST";TAB(13)
    ;
1280 PRINT#1,"ACTIVITY DESCRIPTION":PRINT#1," NUMBER"
1290 T$="-":GOSUB 1470:C1=0:FOR J=1 TO Z1:A1=FNA(A(J,17)):
    GOSUB 2760:C9$=A1$

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1300 PRINT#1,TAB(5-LEN(STR$(A(J,1))));A(J,1);TAB(12-LEN(STR$(
    (INT(A(J,2)))))
1310 PRINT#1,INT(A(J,2));TAB(19-LEN(C9$));C9$;TAB(10);A$(J
    );CHR$(13);
1320 C1=C1+1:IF C1=5 THEN PRINT#1:PRINT#1:C1=0
1330 NEXT:GOSUB 1470:PRINT#1
1340 PRINT#1,TAB(33);"CRITICAL PATH":PRINT#1,TAB(33);"-----
    ":PRINT#1
1350 PRINT#1,E(1);:C9=2:FOR J=2 TO Z1:IF E(J)=0 THEN J=Z1:
    GOTO 1380
1360 PRINT#1,"-";E(J);:C9=C9+2+LEN(STR$(E(J)))
1370 IF C9>75 THEN C9=0:PRINT#1:PRINT#1
1380 NEXT:PRINT#1:PRINT#1:PRINT#1:PRINT#1:PRINT#1:CLOSE 1:
    RETURN
1390 IF F8=1 THEN 1460
1400 OPEN 1,4:PRINT#1:PRINT#1:PRINT#1,"PROJECT";TAB(25);"P
    ROJECT COSTS"
1410 PRINT#1,"DURATION":PRINT#1,TAB(16);"INDIRECT";TAB(13)
    ;"DIRECT";TAB(14);
1420 PRINT#1,"TOTAL":PRINT#1:A1=FNA(C):GOSUB 2760:C2$=A1$:
    A1=T*A(1,12)
1430 GOSUB 2760:C3$=A1$:A1=A1+FNA(C):GOSUB 2760:C4$=A1$
1440 PRINT#1,TAB(5-LEN(STR$(T)));T;TAB(18-LEN(C3$));C3$;TAB(
    19-LEN(C2$));C2$;
1450 PRINT#1,TAB(19-LEN(C4$));C4$:PRINT#1,CHR$(19):CLOSE 1

1460 F8=F9:RETURN
1470 PRINT#1:FOR I=1 TO 80:PRINT#1,T$;:NEXT:PRINT#1:PRINT#
    1:RETURN
1480 REM *****
1490 REM ***** PICK CRITICAL ACTIVITY TO SPEED UP *****
1500 REM *****
1510 IJ=0:FOR I=1 TO Z1:J=E(I):IF J=0 THEN I=Z1:GOTO 1540
1520 IF A(J,2)-A(J,18)<1 OR A(J,20)=0 THEN 1540
1530 IF IJ=0 OR A(IJ,20)+M(IJ)>=A(J,20)+M(J) THEN IJ=J
1540 NEXT:IF IJ=0 THEN QT=1:T=0:S9=S9-1:RETURN
1550 GOSUB 1560:RETURN
1560 REM *****
1570 REM ***** SPEED UP ACTIVITY IJ *****
1580 REM *****
1590 PRINT "[CLR]"
1600 PRINT "[CUD][CUD][CUD]SPEED ACTIVITY",IJ
1610 PRINT "[CUD]COST INCREASE";FNA(A(IJ,20))
1620 PRINT "[CUD]PLUS ESTIMATE";FNA(M(IJ))
1630 IF V9$<>"S" AND F9=1 THEN GOSUB 1760
1640 IF A(IJ,2)<=A(IJ,18) THEN A(IJ,20)=0:RETURN
1650 A(IJ,2)=A(IJ,2)-1:A(IJ,17)=A(IJ,17)+A(IJ,20):R(IJ)=A(
    IJ,20)
1660 IF A(IJ,2)<=A(IJ,18) THEN A(IJ,20)=0:RETURN
1670 N=18:IF A(IJ,2)>A(IJ,13) AND A(IJ,13)>=A(IJ,18) THEN
    N=13
1680 IF A(IJ,2)>A(IJ,15) AND A(IJ,15)>=A(IJ,18) THEN N=15
1690 A(IJ,20)=(A(IJ,N+1)-A(IJ,17))/(A(IJ,2)-A(IJ,N))
1700 N2=1+A(IJ,2)-A(IJ,18)
1710 IF N2<3 THEN 1740

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1720 FOR K=1 TO 10:IF IJ=PJ(K,1) THEN A(IJ,20)=PJ(K,N2-1)-
    PJ(K,N2)
1730 NEXT
1740 IF A(IJ,20) <=0 AND A(IJ,2) > A(IJ,10) THEN 1000
1750 RETURN
1760 IF C5<>0 THEN 1820
1770 OPEN 1,4:PRINT#1,CHR$(147)
1780 PRINT#1,TAB(7);"SPEED";TAB(10);"COST";TAB(10);"PLUS";
    TAB(9);"RELAX";
1790 PRINT#1,TAB(9);"COST"
1800 PRINT#1,TAB(6);"ACTIVITY";TAB(6);"INCREASE";TAB(6);"E
    STIMATE";TAB(6);
1810 PRINT#1,"ACTIVITY";TAB(6);"SAVING":PRINT#1:PRINT#1
1820 A1=FNA(A(IJ,20)):GOSUB 2760:C2$=A1$:A1=FNA(M(IJ)):GOSUB
    2760:C3$=A1$
1830 PRINT#1,TAB(11-LEN(STR$(IJ)));IJ;TAB(16-LEN(C2$));C2$
    ;TAB(14-LEN(C3$));
1840 PRINT#1,C3$:C6=C6+1:IF C6=5 THEN PRINT#1:PRINT#1:C6=0

1850 C5=1:RETURN
1860 A1=FNA(A(IJ,20)):GOSUB 2760:C2$=A1$
1870 PRINT#1,TAB(53-LEN(STR$(IJ)));IJ;TAB(14-LEN(C2$));C2$
    :C6=C6+1
1880 IF C6=5 THEN PRINT#1:PRINT#1:C6=0
1890 RETURN
1900 REM *****
1910 REM ***** NO REDUCTION POSSIBLE *****
1920 REM *****
1930 PRINT "[CLR][CUD][CUD][CUD][CUD][CUD] NO FURTHER
    REDUCTION POSSIBLE"
1940 PRINT "[CUD][CUD] ALL CRITICAL ACTIVITIES"
1950 PRINT "[CUD] AT CRASH DURATION[CUD][CUD][CUD]
    ":FOR I1=1 TO 4000:NEXT
1960 IF V9$<>"S" AND F9=1 THEN PRINT#1,CHR$(19):CLOSE 1
1970 F7=2:F8=2:F6=2:RETURN
1980 OPEN 1,4:PRINT#1,CHR$(147):PRINT#1,TAB(25);"NO FURTHER
    REDUCTION POSSIBLE"
1990 PRINT#1,TAB(19);"ALL CRITICAL ACTIVITIES AT CRASH DUR
    ATION"
2000 PRINT#1:PRINT#1:PRINT#1:PRINT#1:PRINT#1,"PROJECT";TAB(
    25);"PROJECT COSTS"
2010 PRINT#1,"DURATION":PRINT#1,TAB(16);"INDIRECT";TAB(13)
    ;"DIRECT";TAB(14);
2020 PRINT#1,"TOTAL":PRINT#1:PRINT#1:PRINT#1:PRINT#1
2030 C1=0:FOR I=1 TO S9-1:A1=FNA(CT(I)):GOSUB 2760:C2$=A1$
    :A1=DR(I)*A(1,12)
2040 GOSUB 2760:C3$=A1$:A1=A1+FNA(CT(I)):GOSUB 2760:C4$=A1
    $
2050 PRINT#1,TAB(5-LEN(STR$(DR(I)))):DR(I);TAB(18-LEN(C3$)
    );C3$;
2060 PRINT#1,TAB(19-LEN(C2$));C2$;TAB(19-LEN(C4$));C4$:C1=
    C1+1
2070 IF C1=5 THEN PRINT#1:PRINT#1:C1=0
2080 NEXT
2090 PRINT#1:PRINT#1:PRINT#1:PRINT#1,TAB(26);"***** RUN C
    OMPLETED *****"

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2100 PRINT#1,CHR$(19):CLOSE 1
2110 PRINT TAB(6);"***** RUN COMPLETED *****":RETURN
2120 IF V9$="P" THEN GOSUB 1980:GOSUB 2250:RETURN
2130 PRINT:C1=0:FOR I=1 TO S9-1:IF C1=0 THEN PRINT "[CLR]"

2140 PRINT "PROJECT DURATION",,DR(I):PRINT
2150 C2=FNA(CT(I)):C3=DR(I)*A(1,12):C4=C2+C3
2160 PRINT "PROJECT COSTS    INDIRECT",C3:PRINT
2170 PRINT "                DIRECT",C2:PRINT
2180 PRINT "                TOTAL",C4:PRINT:PRINT
2190 C1=C1+1:IF C1=2 THEN C1=0:GOSUB 2220
2200 NEXT:PRINT "[CUD][CUD][CUD]":IF V9$="B" THEN GOSUB 19
      80:GOSUB 2250:RETURN
2210 GOSUB 2110:GOSUB 2250:RETURN
2220 PRINT "[REV]PRESS[OFF] ANY KEY TO CONTINUE":FOR X7=1
      TO 10:GET Z9$:NEXT
2230 GET Z9$:IF Z9$="" THEN 2230
2240 RETURN
2250 REM *****
2260 REM ***** DATA LISTING ON PRINTER *****
2270 REM *****
2280 PRINT "[CUD][CUD]DO YOU REQUIRE A FULL LISTING ON THE
      "
2290 PRINT "PRINTER OF THE DATA HELD ON DISK ?"
2300 GOSUB 2340:IF Q$="Y" THEN GOSUB 2450:GOSUB 2490:GOSUB
      2550:GOSUB 2600
2310 PRINT "[CLR][CUD]END OF RUN":END:RETURN
2320 OPEN 1,8,15:OPEN 2,8,2,"0:"+F1$+",S,R":GOSUB 2710:INPUT#
      2,Z1:GOSUB 2730
2330 RETURN
2340 PRINT "[CUD][CUD]TYPE Y FOR YES OR N FOR NO[CUD][CUD]
      "
2350 FOR Q1=1 TO 10:GET Q$:NEXT
2360 GET Q$:IF Q$="" THEN 2360
2370 IF Q$<>"Y" AND Q$<>"N" THEN 2360
2380 RETURN
2390 OPEN 1,8,15:OPEN 2,8,2,"0:"+FA$+",S,R":GOSUB 2710:FOR
      J=0 TO 20
2400 FOR I=0 TO Z1:INPUT#2,A(I,J):GOSUB 2730:NEXT I,J:RETURN

2410 OPEN 1,8,15:OPEN 2,8,2,"0:"+FD$+",S,R":GOSUB 2710:FOR
      I=0 TO Z1
2420 INPUT#2,A$(I):GOSUB 2730:NEXT:RETURN
2430 OPEN 1,8,15:OPEN 2,8,2,"0:"+FP$+",S,R":GOSUB 2710:FOR
      I=0 TO 10
2440 FOR J=0 TO 50:INPUT#2,PJ(I,J):GOSUB 2730:NEXT J,I:RETURN

2450 GOSUB 2320:OPEN 1,4:PRINT#1,CHR$(147)
2460 PRINT#1,TAB(32),"DATA HELD ON DISK"
2470 PRINT#1,TAB(32);:FOR I=1 TO 17:PRINT#1,"-";:NEXT:PRINT#
      1:PRINT#1
2480 PRINT#1," NUMBER OF ACTIVITIES";Z1:PRINT#1:PRINT#1:CLOSE
      1:RETURN
2490 GOSUB 2410:OPEN 1,4:PRINT#1," CONTRACT DESCRIPTION"
2500 PRINT#1," _____":PRINT#1:PRINT#1,TAB(1
      );A$(0):PRINT#1

```

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2510 PRINT#1:PRINT#1," ACTIVITY", " ACTIVITY"
2520 PRINT#1," NUMBER", " DESCRIPTION":PRINT#1:PRINT#1
      :C8=0:FOR I=1 TO Z1
2530 PRINT#1,I;TAB(22-LEN(STR$(I)));A$(I):C8=C8+1:IF C8=5
      THEN C8=0:PRINT#1
2540 NEXT:PRINT#1:CLOSE 1:RETURN
2550 GOSUB 2390:OPEN 1,4:PRINT#1:PRINT#1
2560 PRINT#1," NUMERIC DATA REFERENCE NUMBER";A(0,0):PRINT#1
      1:PRINT#1
2570 FOR I=1 TO Z1:A(I,20)=FNA(A(I,20)):FOR J=1 TO 5:FOR Q
      =0 TO 3
2580 PRINT#1,J+Q*5;"-";A(I,J+Q*5);TAB(17-LEN(STR$(J+Q*5)+STR$(
      A(I,J+Q*5))))
2590 NEXT:PRINT#1:NEXT:PRINT#1:PRINT#1:NEXT:CLOSE 1:RETURN

2600 GOSUB 2430:OPEN 1,4:PRINT#1:PRINT#1
2610 PRINT#1," DETAILED COSTING REFERENCE NUMBER";PJ(0,0):
      PRINT#1:PRINT#1
2620 C7=0:FOR I=1 TO 10:C8=0:IF PJ(I,1)=0 THEN C7=C7+1:GOTO
      2690
2630 FOR J=1 TO 11:FOR Q=0 TO 3:PRINT#1,J+Q*13;"-";PJ(I,J+
      Q*13);
2640 PRINT#1,TAB(17-LEN(STR$(J+Q*13)+STR$(PJ(I,J+Q*13)))):
      NEXT:PRINT#1
2650 C8=C8+1:IF C8=5 THEN C8=0:PRINT#1
2660 NEXT:FOR J=12 TO 13:FOR Q=0 TO 2:PRINT#1,J+Q*13;"-";P
      J(I,J+Q*13);
2670 PRINT#1,TAB(17-LEN(STR$(J+Q*13)+STR$(PJ(I,J+Q*13)))):
      NEXT:PRINT#1:NEXT
2680 PRINT#1:PRINT#1
2690 NEXT:IF C7=10 THEN PRINT#1," NO DETAILED COSTING EXIS
      TS"
2700 PRINT#1,CHR$(19):CLOSE 1:RETURN
2710 INPUT#1,EN$,EM$,ET$,ES$:IF EN$="00" THEN RETURN
2720 PRINT "[CUD][CUD][CUD][REV]ERROR ON DISK[OFF][CUD][CUD]
      [CUD]":PRINT EM$,EN$,ET$,ES$:CLOSE 2:CLOSE 1:END
2730 RS=ST:GOSUB 2710:IF RS=0 THEN RETURN
2740 IF RS=64 THEN CLOSE 2:CLOSE 1:RETURN
2750 PRINT "[CUD][CUD][CUD][REV]BAD DISK[OFF] STATUS IS"
      ;RS:CLOSE 2:CLOSE 1:END
2760 A1$=STR$(A1):IF A1=INT(A1) THEN A1$=A1$+".00":RETURN
2770 IF 10*A1=INT(10*A1) THEN A1$=A1$+"0"
2780 RETURN

```

"D"

Item No.

0	Numeric Data Reference No					
1	Activity No (100 max)					
2	Minimum cost duration					
3	Act Nos in ascending order PRECEDENT 1					
4	2					
5	3					
6	4					
7	5					
8	6					
9	7					
10	8					
11	9					
12						
13	Intermediate Low Duration					
14	Intermediate Low Duration Cost					
15	Intermediate high Duration					
16	Intermediate high Duration Cost					
17	Minimum Cost					
18	Crash Duration					
19	Crash Cost					
20	Derived by Program					

"H" Indirect Cost per time Unit

--	--

"N" Contract Description

--	--

Activity Description

--	--

(999 is Placed by program in item after last precedent, except when there are 9 precedents)

Input No	Cost Ref No	Sheet 1 of 2									
Activity No											
From INCRIT	Cc at Cd	Dur	Cost	Dur	Cost	Dur	Cost	Dur	Cost	Dur	Cost
From INCRIT	Mc at Mcd										
	Cost at Cd +1 time unit										
	Cost at Cd +2 time units										
	Cost at Cd +3 time units										
	Cost at Cd +4 time units										
	Cost at Cd +5 time units										
	Cost at Cd +6 time units										
	Cost at Cd +7 time units										
	Cost at Cd +8 time units										
	Cost at Cd +9 time units										
	Cost at Cd +10 time unit										
	Cost at Cd +11 time unit										
	Cost at Cd +12 time unit										
	Cost at Cd +13 time unit										
	Cost at Cd +14 time unit										
	Cost at Cd +15 time unit										
	Cost at Cd +16 time unit										
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	Cost at Cd +18 time unit										
	Cost at Cd +19 time unit										
	Cost at Cd +20 time unit										
	Cost at Cd +21 time unit										
	Cost at Cd +22 time unit										
	Cost at Cd +23 time unit										

	Cost at Cd +24 time unit								
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	Cost at Cd +29 time unit								
	Cost at Cd +30 time unit								
	Cost at Cd +31 time unit								
	Cost at Cd +32 time unit								
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	Cost at Cd +40 time unit								
	Cost at Cd +41 time unit								
	Cost at Cd +42 time unit								
	Cost at Cd +43 time unit								
	Cost at Cd +44 time unit								
	Cost at Cd +45 time unit								
	Cost at Cd +46 time unit								
	Cost at Cd +47 time unit								
	Cost at Cd +48 time unit								
	Cost at Cd +49 time unit								
	Cost at Cd +50 time unit								

## BIBLIOGRAPHY

- 1 LAREW Dr R E. Preventing or Mitigating the Effects of Construction Delays. Proceedings of the CIB W-65 Second Symposium on Organisation and Management of Construction. Vol.1, Session II, Page 231. 1978.
- 2 MEYRAN Dr G. Interrelationship of Research and Practice. Proceedings of the CIB W-65 Second Symposium on Organisation and Management of Construction. Vol.1, Session II, Page 267. 1978.
- 3 BJORNSSON H C. The Numbers Game: Quantitative Techniques in Construction Management. Proceedings of the CIB W-65 Second Symposium on Organisation and Management of Construction. Vol.1, Session II, Page 73. 1978.
- 4 GIL A. Discussion Paper Vol.IV, Session II, Page 93. Proceedings of the CIB W-65 Second Symposium on Organisation and Management of Construction. 1978.
- 5 POPESCU C. Pitfalls of GSA. CMCS Software. ASCE. Journal Of the Construction Division. 1978.
- 6 HARPER D. Building - The Process and the Product. Construction Press. 1978.
- 7 RICS/NFBTE. Standard Method of Measurement. 6th Edition. 1978.
- 8 SRC. Building Economic Research Unit Report. 'Building' July 1978
- 9 FRIEDMAN L. A Competitive Bidding Strategy. Operations Research. Vol.4. pp 104-112. 1956.
- 10 RUBEY H & MILNER W. Construction & Professional Management. MacMillan. 1966.
- 11 BANWELL H. The Placing & Management of Contracts for Building and Civil Engineering Work. HMSO. 1964.
- 12 Chartered Institute of Building. Code of Estimating Practice. 1966.
- 13 HIGGINS G & JESSOP N. Interdependence and Uncertainty - A Study of the Building Industry. Tavistock Institute Report. London 1966.
- 14 JAQUES E. Measurement of Responsibility. Tavistock Publications. Harvard United Press. Mass. 1956.
- 15 SANDERS F. On Subjective Probability Forecasting, Journal of Applied Meteorology 2. pp 191-201. 1963.
- 16 ROSS J E. Management by Information Systems. Prentice Hall. 1970.
- 17 MacCRIMMON K. Elements of Decision Making - Theory & Decision. MacMillan, London. 1970 (Eds. K Borch & J Mossin. Risk and Uncertainty)  
MacCRIMMON K. Decision Making Among Multiple Attribute Alternatives - A Survey and Consolidated Approach. Memorandum RM 4823-ARPA. 1968.
- 18 LINDBLOM C E. A Strategy of Decision. The Free Press, NY. 1970.
- 19 MARCH J G & SIMON H A. New Science of Management Decision, American Book Organisations. Stratford Press. 1960.

- 20 CYERT R & MARCH J G. A Behavioural Theory of the Firm. Englewood Cliffs. NJ. Prentice Hall. 1963.
- 21 KNIGHT F. Risk, Uncertainty and Profit. Boston. Houghton Mifflin. 1921.
- 22 HOWARD R. Decision Analysis: Applied Decision Theory. D B Hertz & J Melese (Eds). Proceedings of the Fourth International Conference on Operational Research. NY. pp 55-71. Wiley. 1966.  
  
HOWARD R. The Foundations of Decision Analysis. IEEE Transactions on Systems Science and Cybernetics. SSC-4. Pages 211-219. 1968.
- 23 RAIFFA H. Decision Analysis. Reading, Mass. Addison-Wealey. 1968.
- 24 SCHLAIFER R. Analysis of Decisions under Uncertainty. McGraw Hill. 1969.  
  
SCHLAIFER R. Probability and Statistics for Business Decisions. McGraw Hill. 1959.
- 25 ADRIAN J. Quantitative Methods in Construction Management. Elsevier. 1973.
- 26 GATES M. Statistical and Economic Analysis of a Bidding Trend. ASCE Proceedings. Vol. 86. No. C03. 1960.
- 27 WEINBERG S. Project Organisation as Effected by Construction Management. Proceedings of the CIB W-65 Second Symposium on Organisation and Management of Construction. 1978.
- 28 STEINER G. Top Management Planners. Collier MacMillan, Canada. 1969.
- 29 KOONTZ H & O'DONNELL C. Principles of Management. Fourth Edition. McGraw Hill. NY. 1968.
- 30 URWICK L. The Elements of Administration. Harper & Row. 1943.
- 31 SPRIEGEL W R & MYERS C E (Eds). The Writings of the Gilbreths. R D Irwin Inc. Ill. 1953.
- 32 'BUILDING' Cost File, Building Cost Information Service.
- 33 LAXTONS. Building Price Book 1980. Kelly Directories Ltd. Ed. N Wheatley. East Grinstead.
- 34 SPON. Architects & Builders Price Book (ed) Davis, Belfield & Everest SPON E & F N.
- 35 GEARY R. Work Study Applied to Building. Tonbridge Printers. 1962.
- 36 MODER J & PHILIPS C. Project Management with CPM & PERT. Van Nostrand Reinhold. 1970.
- 37 MACCRIMMON K & RYAN G. An Analytical Study of the PERT Assumptions Operations Research 12, No.1. pp 16-37.
- 38 CAMPBELL D. Schedule Risk Analysis, Proceedings of the Fourth Annual Seminar Symposium. Project Management Institution. 1972.
- 39 KLINGEL A R. Bias in PERT Project Completion Time Calculation for a Real Network. Management Science. Vol.13. No.4. 1966.

- 40 CRANDALL K. Probabilistic Time Scheduling. Journal of the Construction Division. ASCE Vol. 102. No C03. Proceedings Paper 12398. 1976.
- 41 VAN SLYKE R. Monte Carlo Methods and the PERT Problem. Operations Research Vol. 11. No.5. 1963.
- 42 PEER S & ING Dr C. Expansion of CPT (Construction Planning Technique). Proceedings of the CIB W-65 Second Symposium on Organisation and Management of Construction. 1978.
- 43 STONE P A. Building Design Evaluation, Costs in Use. Spon. 1967.
- 44 HACKEMER G C & FINE B. A Computer Simulation for Estimating and Bidding Strategy. Paper presented at the City University, Decision Making for Bidding and Tendering Conference. 1970.
- 45 GUREL N & ARMON D. Standard Descriptions of Construction Items as a Medium of Information Transfer in the Construction Process. Proceedings of the CIB W-65 Second Symposium on Organisation and Management of Construction. 1978.
- 46 GREEN M. Construction Cost Forecasting. The Potential for using simple Probability Techniques. Proceedings of the CIB W-65 Second Symposium on Organisation and Management of Construction. 1978.
- 47 THURNER G. Probabilistic Aspects in Estimating Construction Costs. Proceedings of the CIB W-65 Second Symposium on Organisation and Management of Construction. 1978.
- 48 CUSACK M M. Small Line Concrete Pumping: An Evaluation of Criteria for Selection and the possible Modification of Construction Methods. CNA A Thesis for MPhil. Lanchester Polytechnic. 1973.
- 49 BELLMAN R E & KALABA R E (eds) Dynamic Programming and Modern Control Theory. Academic Press. 1966.
- 50 KELLEY J E & WALKER M R. Critical Path Planning and Scheduling. Proceedings of the Eastern Joint Computer Conference. 1959.  
KELLEY J E. CPM Mathematical Basis. Vol.9. Part 3. pp 296-319. 1961.
- 51 MALCOLM D G, ROSEBOOM C E, CLARK C E, & FAZAR W. Application of a Technique for Research and Development Program Evaluation. Operations Research Vol.7. pp 646-699. 1959.
- 52 CLARK C E. The PERT Model for the Distribution of an Activity Time. Operations Research. Vol.10. No.3. May/June 1962.
- 53 FONDAHL J W. A Non Computer Approach to the Critical Path Method. Technical Report No.9. Department of Civil Engineering, Stanford University, California. 1961.
- 54 MEYER W L & SHAFFER L R. Extending GBM for Multifarm Project Time Cost Curve. Proceedings of the American Society of Civil Engineers Journal of the Construction Division. Vol.91. No C01. 1965.
- 55 BUTCHER W. Dynamic Programming for Project Cost Time Curves. Journal of the Construction Division. Proceedings of the American Society of Civil Engineers. Vol.93. 1967.



- 56 ROBINSON D D. A Dynamic Programming Solution to Cost Time Trade Off for CPM. Management Science, Vol.22. No.2. 1975.
- 57 FULKERSON D. A Network Flow Computation for Project Cost Curves. Management Science Vol.7. No. 2. pp 167-179. Baltimore. 1961.
- 58 MARKOWITZ H M & MANNE A S. On the Solution of Discrete Programming Problems. Econometrica, North Holland Pub. Co. Amsterdam-C. The Netherlands. Vol.25. 1957.
- 59 ARDITI D. Problems in the Process of Introducing Network Analysis. Proceedings of the Fifth International Congress, Haifa. 1978.
- 60 DOE/PSA. Computing and Communication in the Construction Industry. Produced by the National Consultative Council of the Building and Civil Engineering Industries, Standing Committee on Computing and Data Coordination. 1979
- 61 Ministry of Public Buildings and Works. Computers for Contractors in the Building Industry. 1969.
- 62 Loughborough University of Technology. A Survey of the Use of Computers in the Construction Industry. 1968.
- 63 DESIGN OFFICE CONSORTIUM. Evaluation Report No. 4. Computer Programs for Construction Management. ISBN. 1980.
- 64 KUEHN A A & HAMBURGER M.J. A Heuristic Program. Management Science Vol.9. pp 646-666. 1963.
- 65 CIAD CONSORTIUM. The Effective Use of Computers within the Building Industries of the European Community. European Community Study T/1/77 1979.
- 66 BHANDARI N. Computer Application in Construction Management Journal of the Construction Division. ASCE. Vol.103. NO.CO3. pp 343-356. 1977.
- 67 JENSEN K & WIRTH N. Pascal User Manual and Report. The Second corrected reprint of the second edition. Springer Verlag, NY. 1978.
- 68 KAUFMAN G M & THOMAS H (Eds). Modern Decision Analysis. Penguin.1977.
- 69 CASTLES F, MURRAY D, POTTER D & POLLITT C. Decisions, Organisations and Society. Penguin 1976.